Figure 3.16. Gigantic waves produced by Typhoon Dale in November 1996 as it moved southwest of Guam. The tops of the wave running up the face of cliffs at Orote Point are more than 100 feet high.

Figure 3.17. Erosion and scouring caused by "green" sea water being forced more than 80 feet up the face of a cliff at the South Tipalao housing area, Orote Peninsula, Naval Activities, Guam.

showed unacceptable bacteria levels at Talofofo Bay, Merizo Pier, Toguan Bay, Umatac Bay, Nimitz Beach, Agat Bay, Namo Beach, Asan Bay, and Dungca's Beach (13 Sept 1998 PDN).

3.11. SLOPE FAILURES

Historically, slope failures in the form of *rockslides*, *mudflows* and *debris flows* have not been a serious hazard on Guam in terms of threatening people's lives. This is slowly changing as more and more people build homes in vulnerable areas. The slope failure threat comes from the combination of seismic forces and rainfall. These forces don't necessarily have to work at the same time, and in most cases don't. In general, seismic forces destabilize a slope, then rain saturates the destabilized soil until it begins to slide over itself, often at high speed, creating mudflows (Siegrist 1998). These can move down valleys, gathering debris. In addition, the force of runoff from heavy rain can dislodge loose rocks, causing rockslides. The greatest direct threat is that the path of the mud, rocks or debris will move through houses or villages. The greatest indirect threat is that the flow will temporarily dam drainage, then give way, causing down-stream flooding. Table 3.8 indicates the areas of Guam most vulnerable to slope failure.

Table 3.8. Locations in southern Guam vulnerable to slope failures.

[redacted]	**La Sa Fua River Valley between Umatac and Cetti Bay (Facpi Formation)**
	Between Cetti Bay and Agat transfer station on both east and west side of Route 2, and down both sides of Cetti and Sella Bays (Facpi For.)
	Foothills south of the Villages of Agat and Santa Rita below Mt Alifan-Mt Lam Lam ridgeline (Alutom For.)
	West of Agat Transfer Station in the upper Talaeyag and Talayfac River basin (Facpi For.)
	Big Guatali watershed on west side of Mt. Tenjo in Santa Rita (Alutom For.)
	Apra Heights along the Cross Island Road (Alutom For.)
	Nimitz Hill north side toward Adelup (Alutom For.)
	Inarajan Valley Badlands area west of Inarajan-Laolao River confluence (Bolanos For.)
	North slopes of Talofofo River Valley, southeast of Talofofo Golf Resort
	Ugam-Bubulao Badlands area

4. THE TROPICAL CYCLONE RISK FOR GUAM

4.1. GENERAL

With respect to disasters, ***risk* is the probability that an event will occur.** Risk can be expressed in specific numeric values or in relative terms. Specific numeric values or quantitative probabilities for tropical cyclones (TCs) are presented as recurrence intervals or strike probabilities. Probabilities given in relative or qualitative terms often have the form of more general descriptions such as *low risk*, *average risk*, or *high risk*. Recurrence intervals/return periods are best computed by statistical models. One such model, designed to determine return periods in tropical cyclones, is the HURISK model.

Guam has the highest probability or risk for being hit by a typhoon or hurricane of any state or territory in the United States. Because of the Island's high threat of getting hit by a typhoon, it is paramount that the Island be better prepared to respond to, and to recover from, the effects of a typhoon/hurricane as any other locale in the United States.

4.2. THE HURISK MODEL

4.2.1. General background

Several sources of data and analyses are used to determine the TC risk to Guam. However, the primary tool used was the HURISK Model. The HURISK (Hurricane Risk) Model was developed in 1987 by Science Applications International Corporation (SAIC) for the National Oceanic and Atmospheric Administration (NOAA) Tropical Prediction Center (formerly the National Hurricane Center) at Miami, Florida. Technical aspects of the early version of the program are given in Neumann (1987). Since that time, SAIC has continually improved on the technical and cosmetic aspects of the program. Program output now consists of 21 charts and diagrams that completely describe the TC climate and characteristics of any given site.

HURISK requires many data bases. Included are historical tracks of TC location and intensity, information on radius of maximum winds (RMW), time and location of landfall, rate of storm decay after landfall (not much of an issue with Guam), etc. Originally, HURISK was developed for the Atlantic basin, but primarily due to insurance interests, the program was expanded to cover the eastern and western North Pacific basins. Some features in the adaptations of the model, such as radial wind profiles, are still tuned for the Atlantic basin. Thus, the Model may not be as reliable for the Pacific basins as for the Atlantic. Despite these shortfalls, HURISK is one of the most developed and comprehensive models for determining TC risk in the western North Pacific.

4.3. A REVIEW OF SOME CHARACTERISTICS OF TROPICAL CYCLONES

4.3.1. Measurement units, definitions, etc.

TC winds in HURISK are expressed in knots (kt) and distances are given in nautical miles (n mi or nm). Conversion factors to some other units are:

- Multiply knots by 1.152 to obtain miles per hour (mph);
- Multiply mph by 0.868 to obtain knots;
- Multiply nautical miles by 1.152 to obtain statute miles;
- Multiply statute miles by 0.868 to obtain nautical miles;
- Multiply knots by 1.853 to obtain kilometers per hour;
- Multiply knots by 0.515 to obtain meters per second.

Engineering interests often use the somewhat archaic unit fastest-mile. The conversion factor in going from fastest-mile to other units varies with speed. Below 60 mph, the fastest-mile unit is lower than mph, while above 60 mph, it is larger.

The term *tropical cyclone* refers to all rotating storms (counter-clockwise in the northern hemisphere) of tropical origin regardless of intensity. In the weak stages, these storms are called *tropical depressions*. They are designated as *tropical storms* when the maximum sustained wind near the center reaches at least 34 knots (39 mph). In the western North Pacific, these storms are called *typhoons* when the wind reaches at least 64 knots (74 mph) near the center. The JTWC also uses the term *super typhoon* to describe typhoons where the maximum wind is at least 130 knots (150 mph). TCs that fail to reach at least tropical storm intensity are not formally named by the Joint Typhoon Warning Center and are not directly used in the HURISK analysis.

In keeping with the practice in the US, the winds discussed in the HURISK Model, unless otherwise noted, are near surface (about 33 feet elevation) and the speed is averaged over a 60-second period. These are also referred to as *1-minute sustained winds* or 1-minute averages. Shorter duration gusts/lulls (for example, a brief 2-second gust) can be much higher/lower than the wind averaged over one minute. HURISK uses the standard over-land gust factor of 1.28 in converting from a 1-minute average wind to a 2-second gust (Krayer and Marshall 1992). Thus, a sustained wind of about 50 knots (58 mph) could be accompanied by typhoon force gusts (50 X 1.28 = 64 (74 mph)) of short duration. In some cases, gust factors can be higher or lower than 1.28. Gust factors tend to be lower over water than over land and lower in deep convection than in shallower convection.

The TC data set used for this study includes maximum sustained 1-minute winds at 6-hourly intervals throughout the life of the storm. Winds in TCs are seldom measured with the degree of precision implied by the definitions. This is because the area of maximum wind will seldom move directly over a wind measuring device. Also, such devices that happen to be in the path of a storm will fail due to power outages, damage by flying debris, or mechanical failure. Consequently, winds contained in the HURISK data set and in similar data sets are often estimated from indirect evidence such as satellite imagery, pressure, storm surge, damage, and occasionally by meteorological judgment.

4.3.2. Wind patterns in tropical cyclones

Maximum winds typically occur a few miles radially outward from the inner edge of the eye wall cloud of a TC with the average diameter of the "eye region" (eye + 2 X eye wall cloud) being 25 to 60 n mi. The diameter of the eye is highly variable, and in the region of Guam, can range from less than 10 n mi to more than 50 n mi. Very intense TCs (e.g., Super Typhoon Tip (Oct 1979)) and very small (midget) TCs (e.g., Typhoon Brian (Oct 1992)) can have very small eyes, on the order of 8 n mi. However, TCs with large eyes of 40 n mi or more can also be very intense (e.g., Super Typhoons Yuri (Nov 1991) and Paka (Dec 1997)). The thickness of the eye wall cloud is also highly variable. Intense TCs generally have thicker eye wall clouds in the realm of 10-15 n mi, but Super Typhoon Keith (Nov 1997) had an eye wall cloud little more than 6 n mi across.

Outward from the maximum wind zone, rotational winds diminish fairly rapidly, but the rate depends on a number of factors that can be quite different from one storm to another. For an average storm with maximum winds near the center of say, 100 knots, over-water winds will decrease to 1/2 of this value at a distance of approximately 75 n mi outward from the storm center in all directions. Over land, the rate of wind decrease is greater than over water. It is emphasized, however, that there are major variations from one storm to another.

Most TCs are not symmetric in their wind fields. The primary contribution to the asymmetry is the translation speed of a moving TC. In the northern hemisphere, the speed of motion is added to the winds on the right side of the TC (with respect to its motion) and subtracted from the winds on the left side. This alters both the distribution of the maximum winds, which are normally found in the right semicircle, and the extent of the wind field, which is normally larger in the right semicircle. Thus, it makes a significant difference whether the TC passes north or south of the site.

Terrain features, urbanization, and proximity to large marine areas can substantially alter winds over local areas. Normally, land-falling TCs, particularly intense typhoons, weaken rapidly as they move inland away from the sustaining marine environment, but this is not the case for the small island situation. Guam's small size and relatively low terrain contribute little to TC weakening. In fact, several TCs have intensified as they moved across the Island. Also at above ground levels such as with tall buildings and the windward exposures of hills and mountains, winds are typically higher than at the surface reference level of 33 feet as used by HURISK.

4.3.3. Distinction between "winds at site" and "winds near storm center"

In the HURISK charts to be discussed in subsequent paragraphs, reference is made to two types of winds: (1) those near the storm center, and (2) those occurring at the site, itself. The latter winds are estimated from the former. The estimate is based on a number of factors such as the distance from the site to the storm center, the storm intensity, the bearing of the storm from the site, the storm translation speed, frictional wind reduction, etc. Except for local effects, winds at the site are always less than or equal to the maximum wind at the storm center. In the text and in the various HURISK charts to follow, a distinction is always made as to the type of wind being discussed.

4.3.4. *Point probabilities* versus *areal probabilities*

The HURISK Model provides *point probabilities* and *return periods* for a given site. That is, the specified *probabilities* and *return periods* are strictly valid for a designated location. Depending on the gradient of TC occurrence and intensity, these values may or may not be valid for a different location. **For Guam, it will be shown that the expectancy of a given TC-generated wind is slightly greater over the southern part of the Island than over the north. Also, the expectancy of observing this same wind over any part of the Island (*areal probability*) is higher than over any single location (*point probability*).**

In general, the difference between the *point* and the *areal probabilities* depends on the size and the shape of the area under consideration and the orientation with respect to the prevailing approach direction of TCs. Since Guam is oriented more or less perpendicular to the prevailing storm tracks, it is possible that a given storm could produce a given wind on the northern portion of the Island but not on the southern portion and vice versa. (In fact, this virtually always occurs with a storm passage.) Thus, the likelihood of a given wind at any point on the entire Island would be substantially higher than at a given site. If Guam were oriented parallel to the prevailing TC direction, the difference between the *point* and *areal probabilities* would be much lower. Depending on the shape of an area as well as the variation in TC approach direction, there are several methods available for estimating areal probabilities from point probabilities. This will be discussed shortly.

4.3.5. Further Discussion of Radius of Maximum Winds (RMW)

The HURISK Model was initially designed for the Atlantic basin and used radial over-water wind profiles and radii of maximum wind (RMW) values given by Schwerdt et al. (1979) for the Atlantic basin. The question arises here about using these same values in the western North Pacific version of HURISK. In the case of RMW, a large number of western North Pacific RMWs as given in Schwerdt et al. (1979) were also used in developing the Model. Therefore, RMW problems are considered minimal, at least in the mean.

For radial wind profiles, however, western North Pacific profiles are somewhat larger than for the Atlantic, other factors being equal. This is evident in noting that storms passing a large distance south of Guam can bring significant winds to the Island. Indeed, in initially running HURISK for Guam, it was noted that the return periods of given winds seemed somewhat high (less frequent) compared to those implied by data in Tropical Cyclones Affecting Guam (1991) and from Rupp and Lander (1997).

The wind profiles were used in HURISK are over-water profiles as a function of RMW. For large RMWs, a given wind extends a much greater distance from the storm than for small RMWs. When using HURISK for land-based sites, a friction factor is used to reduce these wind profiles. Lowering this has the same effect as magnifying the wind profiles. This was the technique used here to simulate western North Pacific profiles from the Atlantic data.

4.4. GENERAL COMMENTS ON WESTERN NORTH PACIFIC TROPICAL CYCLONE CLIMATOLOGY

4.4.1. Frequency and seasonal variation

The western North Pacific is the most active TC basin in the world. On the average, 28 tropical storms and typhoons occur annually, and this compares to about 10 for the North Atlantic basin. Also, western North Pacific storms tend to be larger and more intense than those in the Atlantic basin. Typhoons with sustained winds over 130 knots (150 mph) -- *super typhoons* -- are reasonably common in the western North Pacific, but are relatively rare over other basins such as the North Atlantic. In 1997, a record number 11 super typhoons were observed in the western North Pacific.

Another distinguishing feature of the western North Pacific basin is that TCs, although most common in late summer and autumn, can occur at any time of the year, whereas over other basins they are more seasonal. The main TC season for the western North Pacific extends from mid-May through mid-December with the peak of the season being July through November. For the basin as a whole, TCs are least likely during the month of February. And surprisingly, Guam has not experienced a typhoon in June, at least since 1945.

4.4.2. Tropical cyclone occurrence in the Guam area

Even though Guam is situated somewhat southeast from the main portion of the western North Pacific TC basin, it is very vulnerable to TCs. Although some areas of the basin such as the relatively unpopulated area of northeastern Luzon in the Philippines observe a higher number of TCs of greater severity, Guam is one of the more heavily populated areas of the world subject to frequent TC events.

The great majority of TCs that affect Guam approach from the ESE and many are in the deepening phase as they pass the Island. These approach directions are addressed in Figure 4.1 and the deepening tendency can be noted in Figure 4.2. In the latter, the point where each of the 194 TCs that passed within 180 n mi from Guam, 1945-1997, became a typhoon can be seen. Note the cluster of TCs that became typhoons just after they passed the closest point of approach to Guam. Had Guam been located a few degrees of longitude westward, its TC climate would be much more severe.

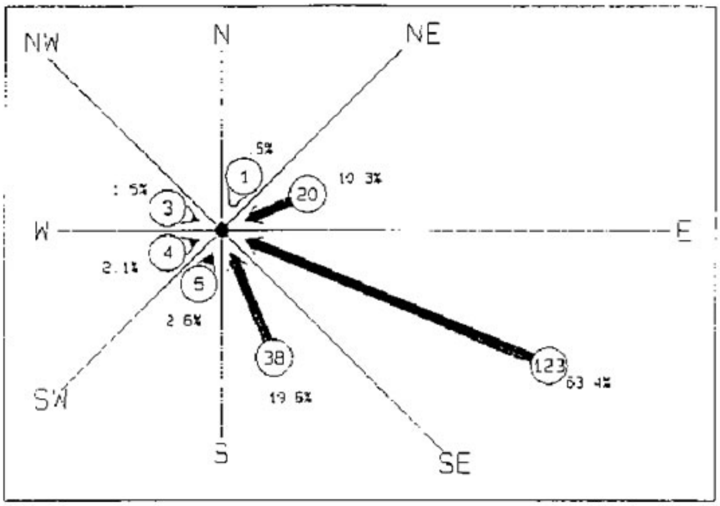


Figure 4.1. Distribution of the approach directions for the 194 tropical storms and typhoons that passed within 180 n mi of Guam, 1945-1997. Arrow length is proportional to frequency, number of cases from each octant are circles, and percentages from each octant are also shown. Direction is at the time of the closest point of approach to the site.

Generally speaking, typhoons that pass within 180 n mi of Guam, particularly to the south, can be expected to have some effect on the site. Those that pass within 75 n mi can be expected to have a much more serious effect. Some of the HURISK findings in regard to TC risk to Guam are given in Table 4.1.

As given in Table 4.1, Guam (Tiyan), over the 53-year period (1945-1997) has observed 71 TCs that have passed within 75 n mi from the site with 33 of these being classified as typhoons. In comparison, Miami, Florida, in the heart of the Atlantic TC basin, observes less than 1/2 of that amount during a similar span of years. The variation in TC frequency is seen to be small over the Island. However, since storms to the south are somewhat stronger on average than those to the north, and the stronger and more extensive winds of the "strong semicircle" are impacting the Island, the expectancy of a given wind force is somewhat higher over the south portions of the Island.

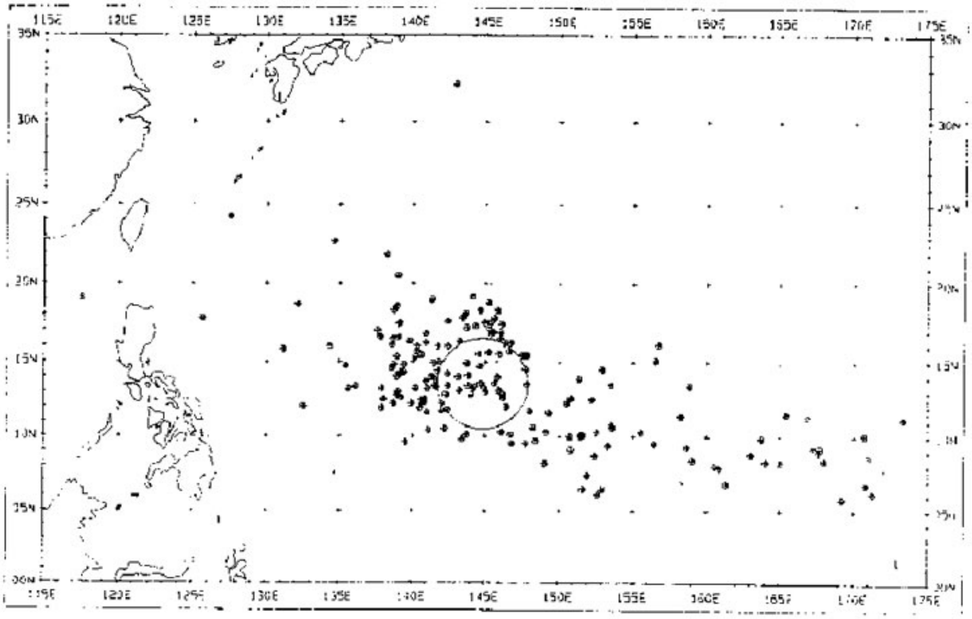


Figure 4.2. For the 194 tropical storms and typhoons that passed within 180 n mi from Guam (circles area), 1945-1997, symbols depict location where typhoon intensity was first attained. Eighteen of the 194 cases never reached typhoon intensity.

4.4.3. Areal Probabilities

Section 4.3.4 gave a brief discussion of point versus *areal probabilities*, the latter being greater than or equal to the former. From Table 4.1, it can be noted that the number of TCs passing within 75 n mi of a single point on Guam is quite similar (69-71 cases). However, these are not necessarily the same groups of storms, and further examination showed that 25 of the TCs and 18 of the typhoons were not common to 75 n mi scans at the extreme north and south ends of the Island. Thus, there are 96 (71+25) TCs and 49 (33+16) typhoons passing within 75 n mi of the Island as a whole. These totals are also shown in Table 4.1. Searching 75 n mi eastward and westward from the coastal points near the center of the Island did not include any additional TCs than those contained in either the north or south group.

Inflating the south Guam probabilities in proportion to the additional number of TCs passing the Island as a whole (96) rather than at south Guam itself (70), gives an estimate of the *return periods* for TC events anywhere over the Island. These island expectancies are also cited in Table 4.1. Using data provided in Tropical Cyclones Affecting Guam (JTWC 1991) and augmented through the 1997 season suggests that the areal values given in Table 4.1 are reasonable.

Table 4.1. Summary of significant tropical cyclone risk factors. In item 5, average headings are toward which the storm is moving. In item 6, this is the approximate mid-season with 1/2 the storms occurring before this date and 1/2 occurring later. Return periods enclosed in parenthesis are approximations only and are not computed by the HURISK Model -- See Section 4.4.3.

1		Site	Ritidian Pt	Tiyan	Merizo	Entire
			(North)	(Central)	(South)	Island
2	a	Site Latitude	13°39'N	13°29'N	13°14.5'N	
	b	Site Longitude	144°52'E	144°48'E	144°42'E	
		Tropical cyclones passing				
		within 75 nautical miles				
		between 1945 & 1997:				
3	a	Tropical storms & typhoons	69	71	70	96
	b	Typhoons only	32	33	36	49
		Return period (years) for				
		sustained site winds of:				
4	a	≥34 knots (tropical storm)	2.3	2.1	2.0	(1.4)
		≥50 knots (gusts to 64 kts)	4.3	3.9	3.8	(2.8)
		≥64 knots (typhoon/hurricane)	7.1	6.4	6.3	(4.7)
		≥100 knots	25.2	22.1	22.3	(16.3)
5		Average heading and speed of				
		typhoons & tropical storms				
		at closest point of approach	293°/12.6	291°/12.5	292°/12.3	292°/12.5
6		Median occurrence date	Oct 05	Oct 03	Sept 30	Oct 02

4.4.4. Interpretation of *return periods*:

Return periods refer to the average recurrence interval of an event. The term is often misinterpreted. For example, consider two sites, A and B. For a given 50-year period, site A might observe five occurrences of some event in the first 10 years and none for the next 40 years. At site B, the event might occur every 10 years over the 50-year period. The return period of the event at both sites would be identical, that is once every 10 years, on the average. TC events often behave more like site A; that is, they tend to occur in clusters rather than at regular intervals (see discussion of Chart 4).

4.5. HURISK ANALYSIS FOR GUAM

4.5.1. Overview

Individual HURISK charts for Guam will be discussed in this section. Some of the more significant HURISK findings for the Tiyan site as well as for the northern and southern sections of the Island were extracted from these charts and presented in Table 4.1. A Summary Table 4.2 also shows pertinent information, extracted from various HURISK charts. Some of the charts are not displayed in the text but are shown in Appendix D.

4.5.2. Discussion of individual HURISK charts

4.5.2.1. Charts 1A and 1B

Chart 1A is the master list of TCs having at least tropical storm intensity while passing within 75 n mi from Guam. Chart 1B is a sub-set of this list containing those TCs that had at least 64 knots of wind while within the 75 n mi area over the 53-year period of record, 1945-1997. These Charts are shown in Appendix D

Column 7 of these charts gives the maximum wind near the storm center -- not necessarily at the site. Here, it can be noted that some of the typhoons, having an asterisk (*) appended to the wind speed, were not classified as typhoons when at the closest point of approach (CPA). Column 8 gives the distance of the storm center from the site at CPA. Unless the storm center passes very near or directly over the site, the winds experienced at the site are typically less than the winds at the storm center.

Column 9 in Charts 1A and 1B gives the direction and the speed of motion of the storm center when it was at CPA. For example, the center of Typhoon Kate, the first storm listed on the chart, was located 69 n mi to the northeast of the site at CPA. At that time, it was moving towards the WNW (303 degrees) at 11.4 knots.

4.5.2.2. Charts 2 and 3

These charts (Appendix D), number 2 for the all-storm category and number 3 for the typhoons-only category, show the tracks of storms listed in Charts 1A and 1B, respectively. As long as a TC is designated as a typhoon in some portion of the 75 n mi zone (not necessarily at the CPA to the site), it is included in Chart 3. Thus, the storms flagged with asterisks on Charts 1A and 1B are also plotted. The tracks include the tropical depression stage (when available) of the TCs.

Most storms are seen to move in from the ESE but exhibit wide dispersion after moving west of Guam. **All else being equal, storms that pass to the south of Guam typically bring higher winds than storms passing the same distance to the north.** This is due to the fact that, for storms passing to the south, the counter-clockwise wind circulation around the storm is augmented by the storm's translation speed. Also, **storms passing to the south tend to be somewhat more severe than those passing to the north (see Chart 18).**

Considering the above, a worst-case scenario for destructive winds at this site would be an intense storm (Typhoon Category 5) that moves slowly from SSW towards the NNE, just west of and parallel to the Island. However, because the dominant steering forces for intense storms are from the ESE to the WNW, such a scenario is unlikely. However, two occurrences come to mind -- Typhoon Olive (Apr 1963) took a northward track just west of the Island and Typhoon Andy (Apr 1989), moving southwest of Guam, turned to the northeast and passed 90 n mi east of the Island. **A more realistic worst-case scenario would be for the center of an intense storm to pass just south of the center of the Island, with the entire Island exposed to the eye wall cloud.** Typhoons Karen (Nov 1962), Pamela (May 1976), and Omar (Aug 1992) are examples, except that Karen moved across the Island at 20 mph, while the other two moved across the Island at less than half that speed. This scenario maximizes the worst case for winds and for west-side storm surge and inundation. **The worst-case for east-side storm surge and inundation would occur where a large, intense, fast moving tropical cyclone moves south of the Island.** Super Typhoon Yuri (Nov 1991) was such a case.

4.5.2.3. Chart 4

This chart illustrates the chronological occurrence of each TC from 1945 through 1997. In this chart, the designation of typhoon or tropical storm is at the time of CPA. Thus, only 28 typhoons are listed here rather than 33 as given in other charts.

The vagaries of TC occurrence are evident from Chart 4. In 1992, there were five typhoons passing within 75 n mi of Guam, while over the 6-year period, 1970-1975, there were no occurrences, not even a tropical storm. In many instances, the probability of these unusual events can be determined through use of the Poisson distribution. However, in applying the distribution to these two events cited above, the probabilities are so low that they approach zero.

These extreme low probabilities are likely related to the fact that use of the Poisson distribution requires that individual events be independent and they may not be. TC formation in this area often takes place on the monsoon trough and extensions of this trough to the east, perhaps associated with large scale fluctuations in ocean temperature, could favor TC chain development to the east of the site -- as occurred in 1992. The lack of a strong trough to the east could have the opposite effect -- as occurred from 1970 through 1975. Thus, the five occurrences in 1992, even though real, are perhaps equivalent to only two or three cases in the purely statistical sense. Similar reasoning, but in the opposite sense, could explain the extremely low probability of the 1970-1975 inactivity. Accordingly, **the use of the Poisson distribution scheme to compute the probability of extreme events is not recommended in the Guam area.**

4.5.2.4. Chart 5

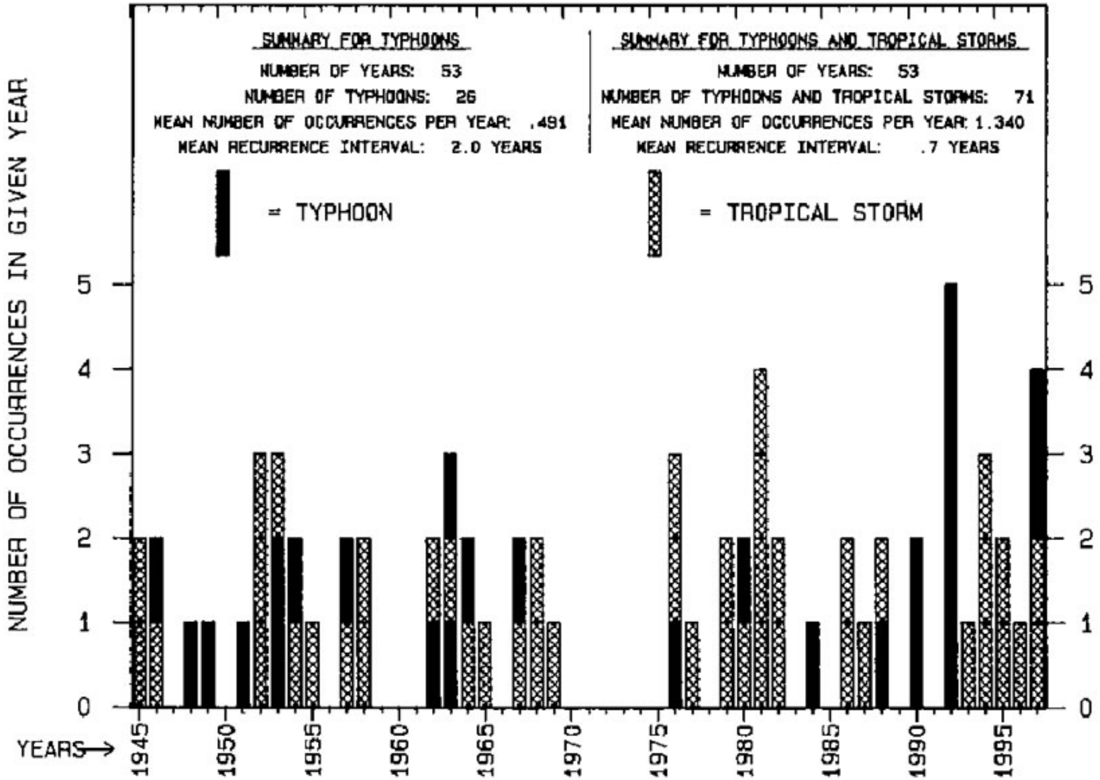
This Chart is a depiction of seasonal variations in TC occurrence for Tiyan. As noted on the chart, **the median date of occurrence is in early October (October 3), although there is a "masked" bi-modal peak in typhoon activity, with a peak in April-May, followed by a lull in June-July, with activity returning in August-September. The peak in typhoon activity is clearly in October-November-December.** The lack/abundance of activity during the weeks of October 22-28/November12-18 might well be aberrations due to the relatively short period of record. It is not prudent to assume that these dates are safer from typhoon threats than dates surrounding them.

4.5.2.5. Chart 6

This Chart shows the directions from and towards which TCs have moved when they pass near Tiyan. Here, it can be noted that about **50% of the TCs approach from a rather narrow window of from 90° to 110° (heading 270° to 290°). Very few approach form the southwest clockwise through the northeast (west and north quadrants).** A polar diagram of approach directions is Figure 4.1 in Section 4.4.2. While the figure suggests a greater frequency from the southeast, **many more TCs come from the east than from the south in the quadrant.**

Also included on Chart 6 are the average vector directions of motion as well as scaler and vector translation speeds. These are seen to be similar regardless of intensity and the small difference is not statistically significant. Thus, a **heading and speed of 291°/12.6 knots (14.5 mph) for the season as a whole is an acceptable average motion for all TCs approaching Tiyan specifically and Guam in general.**

There is a small seasonal variation in TC forward motion. During April and May, storms approach from more of a south to southeasterly direction and the average translation speed is only 8-9 knots (9-10 mph). Highest translation speeds are observed in January and average near 16 knots (18 mph), though the sample is small, 7 cases in 53 years.



CHRONOLOGY OF THE 71
TROPICAL STORMS AND TYPHOONS PASSING WITHIN 75 N Mi OF GUAM (TIYAN), 1945-1997

(Note: Designation as tropical storm or typhoon is at time of closest point of approach to site.)

CHART 4

TROPICAL STORMS AND TYPHOONS PASSING WITHIN 75 N Mi OF GUAM (TIYAN), 1945-1997

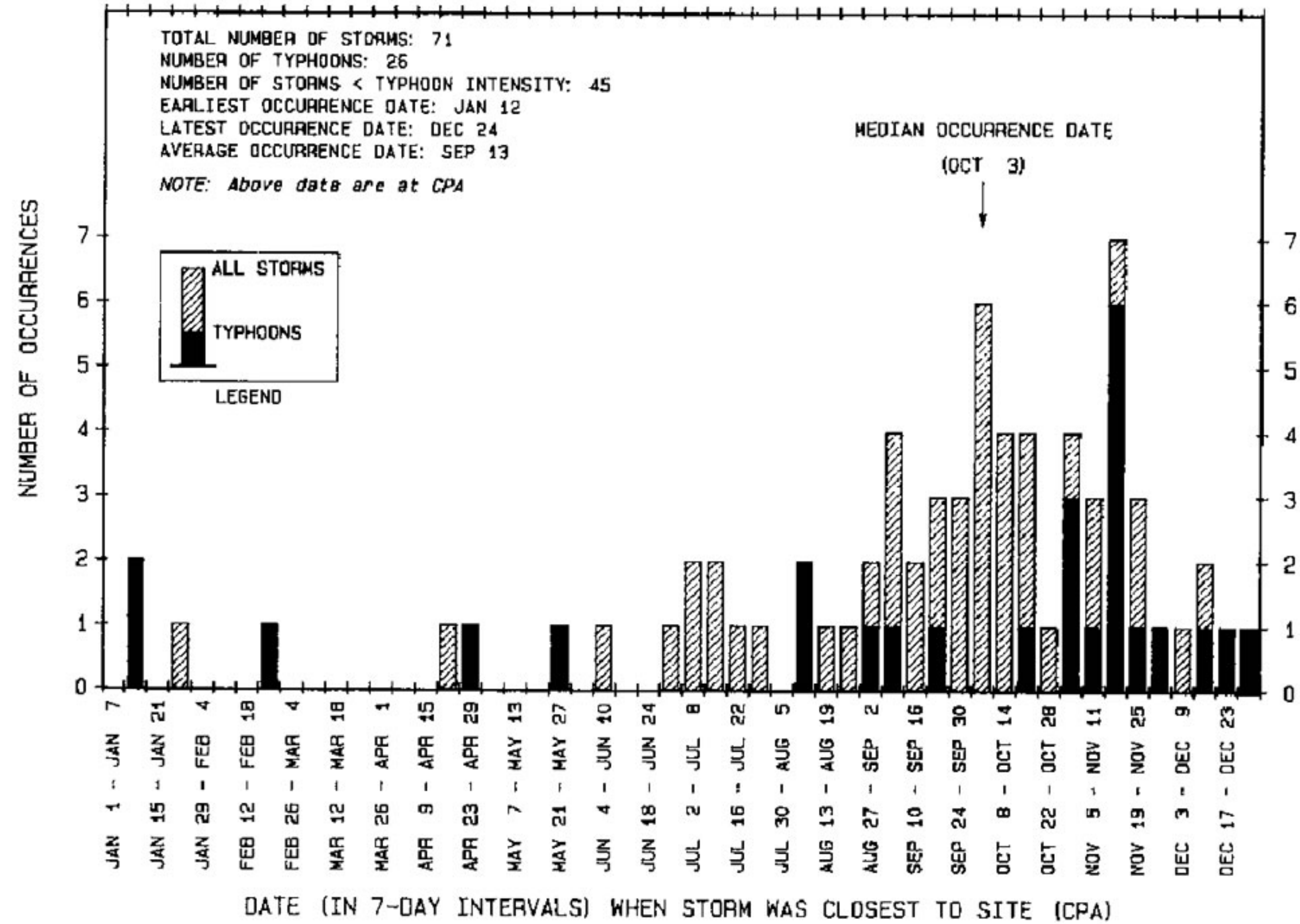


CHART 5

DISTRIBUTION OF STORM HEADINGS FOR

TROPICAL STORMS AND TYPHOONS PASSING WITHIN 75 N Mi OF GUAM (TIYAN), 1945-1997

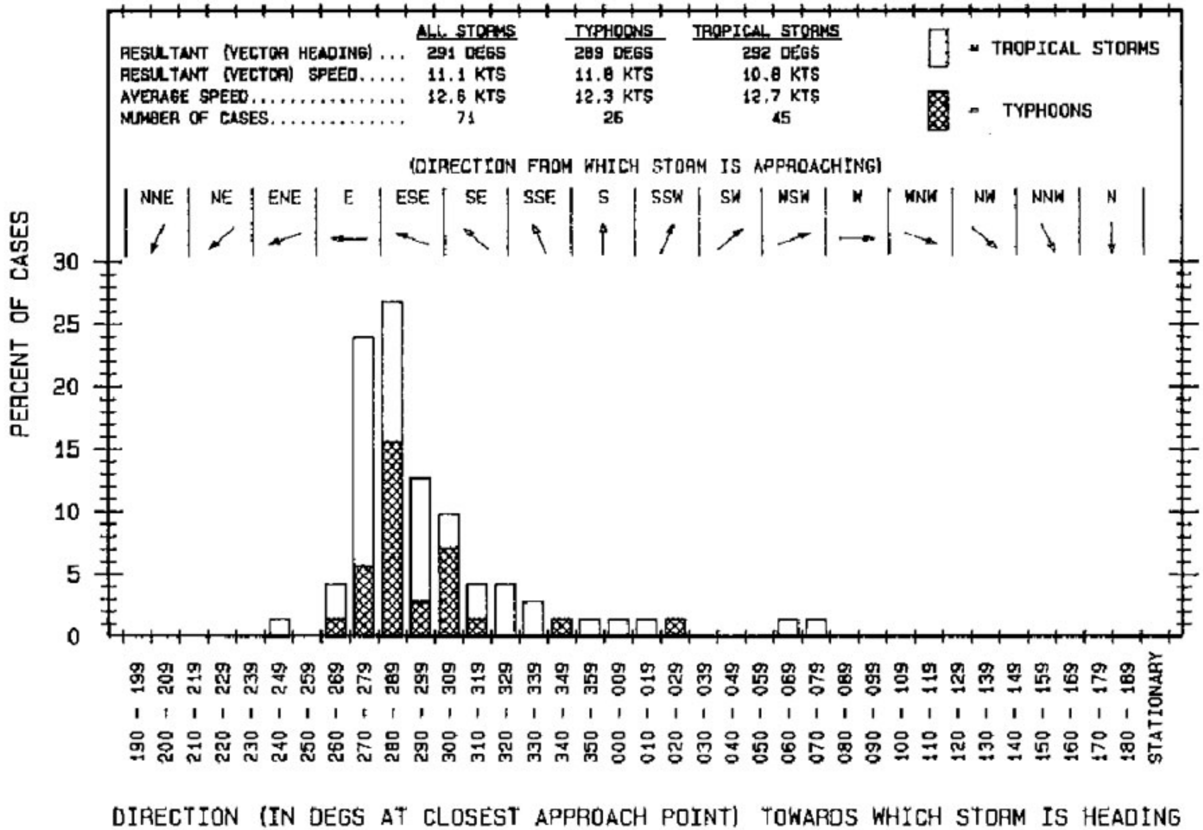


CHART 6

4.5.2.6. Chart 7

This is a depiction of the number of TCs passing at distances less than 75 n mi from Tiyan. The data are taken from column 8 of Chart 1A. In this chart, distance is entered along the lower horizontal scale and the storm count is entered along the vertical scale. The top-right data point represents the 71 storms passing within the 75 n mi radius of Tiyan. At lesser distances, there is a gradual, almost linear decline in the number of TCs passing within that given distance. The mathematical fit to the data on Chart 7 is an important link to the HURISK simulation process. Randomly selected storms used in the Model are forced to conform to this pattern.

The average TC radius of maximum wind (RMW) for Tiyan is seen to be about 13.5 n mi. Storms passing the site within or slightly beyond this distance would likely produce the maximum wind given in column 7 of Charts 1A and 1B at the site. From Chart 1B, it can be noted that several typhoons did pass within that distance. While, as a general rule, very intense storms tend to have a smaller radius of maximum winds, there are many exceptions to the rule. Super Typhoon Yuri (Nov 1991) and Super Typhoon Paka (Dec 1997) both had a RMW in excess of 20 n mi. Many times, intense TCs undergo eye wall cycles where the RMW expands and contracts with the eye wall cloud. Paka's eye wall region went through such a cycle. Yuri's did not. This variability may lead to errors in the Model's output.

4.5.2.7. Chart 8

This is a depiction of the maximum wind in the TCs (as listed in column 7 of Chart 1) when they were at the closest point of approach to Tiyan. The one case of winds between 144 and 154 knots (166 and 177 mph), for example, refers to Super Typhoon Lola of November 1957 that passed 41 n mi south of Tiyan and brought gusts to at least over 100 knots (115 mph) over the southern portion of the Island. Typhoon Russ (Dec 1990) was 25 n mi south of Tiyan and produced 100 kt (115 mph) sustained winds over southern Guam. Super Typhoon Yuri (Nov 1991), which missed the 75 n mi cut-off by 5 n mi, was very large and also produced 100 kt (115 mph) over southern Guam, despite being 80 n mi south of the Island. This type of omission makes the HURISK-generated return periods slightly higher than they should be.

The somewhat ragged nature of the observed data around the best-fit line is typical of most sites in any basin and probably reflects the uncertainty in assigning maximum winds to TCs rather than a bad fit to the data. For example, it is quite possible that a few of the cases in the 54-64 knot (62-74 mph) and the 34-44 knot (39-51 mph) class intervals could have been assigned to the 44-54 knot (51-62 mph) class interval, giving a better fit to the data. For this reason, a mathematical Weibull distribution fit to the data is used in preference to the observed data.

TROPICAL STORMS AND TYPHOONS PASSING WITHIN 75 N Mi OF GUAM (TIYAN), 1945-1997

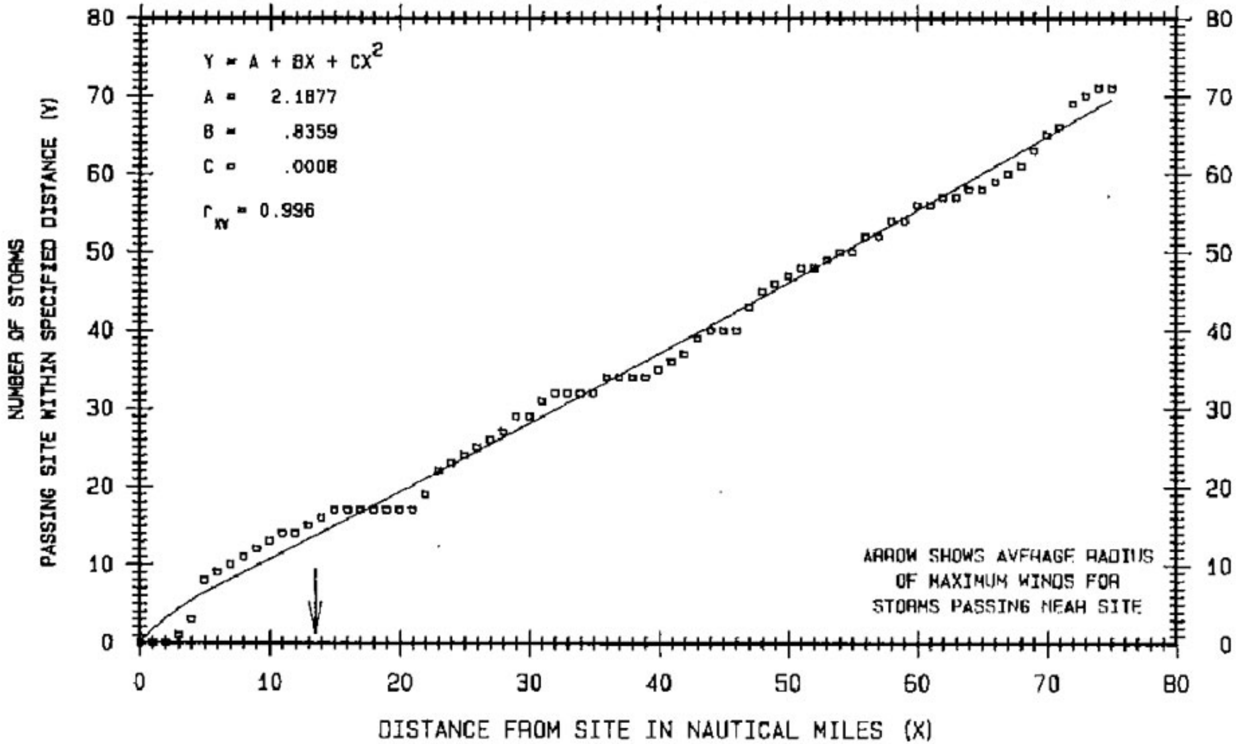


CHART 7

TROPICAL STORMS AND TYPHOONS PASSING WITHIN 75 N Mi OF GUAM (TIYAN), 1945-1997

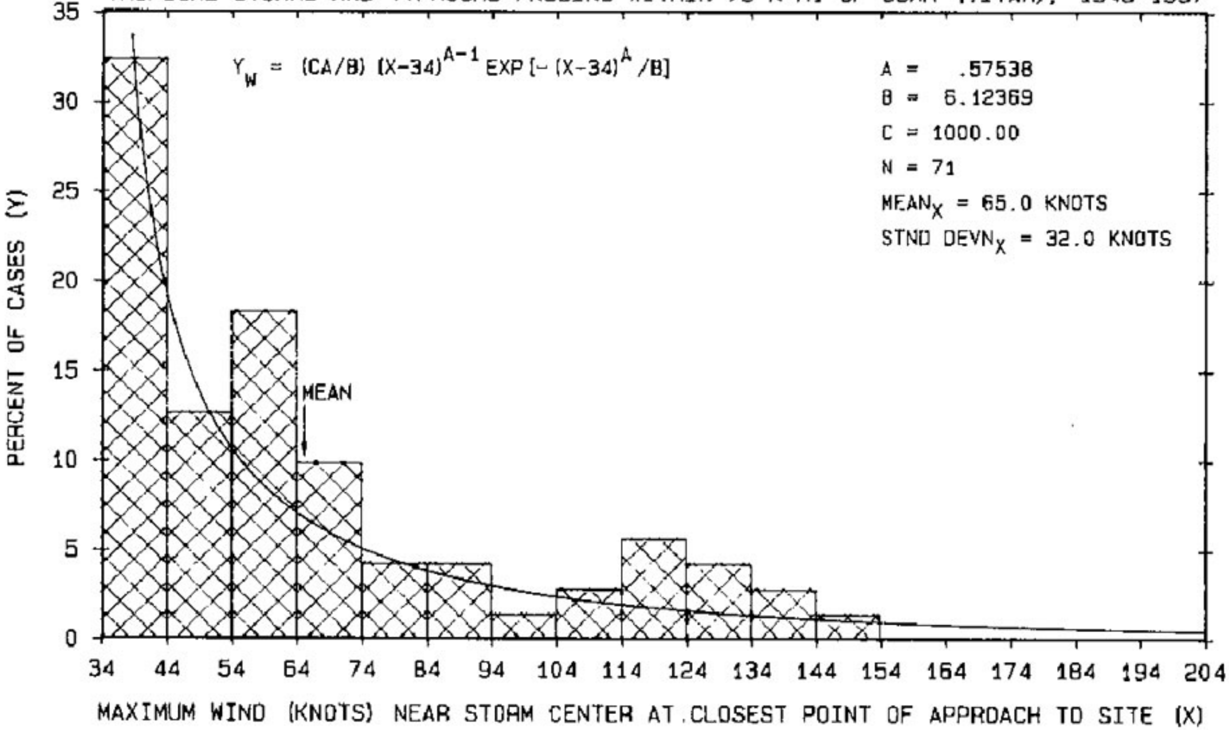


CHART 8

This is another important chart for the HURISK simulation process. Randomly generated TCs are forced to conform to the mathematical fit. Although the curve suggests the possibility of maximum winds reaching to 200 knots (230 mph), the HURISK Model has a cap on the maximum winds of 175 knots (200 mph), and the area under the curve below 175 knots (200 mph) is adjusted to account for the loss of area beyond 175 knots (200 mph). **The selection of a capping wind 175 kt/200 mph varies from site to site, and in effect, is based on climatological sea surface temperature. Guam has the highest values of any basin, and under current sea surface temperature and upper atmospheric temperature conditions, the 175-knot (200 mph) cap is likely the extreme upper limit.**

4.5.2.8. Chart 9A

This chart combines the mathematical fits shown on Charts 7 and 8, and gives the return period of various intensity storms passing at various distances form the site. For example, Chart 9A indicates that storms having at least typhoon force winds near the storm center (see horizontal scale), should pass within 20 n mi from the site (see sloping lines) about once every 9.5 years (see vertical scale). This chart does not address winds at the site itself.

4.5.2.9. Charts 9B and 9C

These charts specifically address TC expected winds at the specified locations whereas Chart 9A refers to the maximum winds near the center of storms as they pass at some distance from the sites. As discussed earlier, the site will not experience the maximum wind unless the storm passes very near the site. Chart 9B represents return period curves for the north (Ritidian Point) and south (Merizo) ends of the Island, while Chart 9C represents the same data for Tiyan. The three curves were not put on the same charts because the Tiyan curve and the south-Guam curve were virtually identical. These data are obtained by simulating 10,000 storms of various intensity, various RMW, and passing within various distances from the site.

To use this chart, select a wind along the bottom horizontal scale and move vertically until intersecting the site curve. Next, proceed to the right vertical scale and read off the return period. For example, 64 knot (74 mph) sustained winds are to be expected, on the average, once every 7.1 years at the north end and once every 6.3 years at the south end. The data presented in Table 4.1 and on the Summary Page (Table 4.2) were extracted from these charts. A return period curve for the Island as a whole is not shown. It is not a part of the standard HURISK packages, but will be less than the return period at the specific sites.

The chart confirms that the TC climate is somewhat more rigorous over the south part of the Island than over the north portion. This is caused by three factors: (1) the number of typhoons passing within 75 n mi is slightly greater over the south than over the

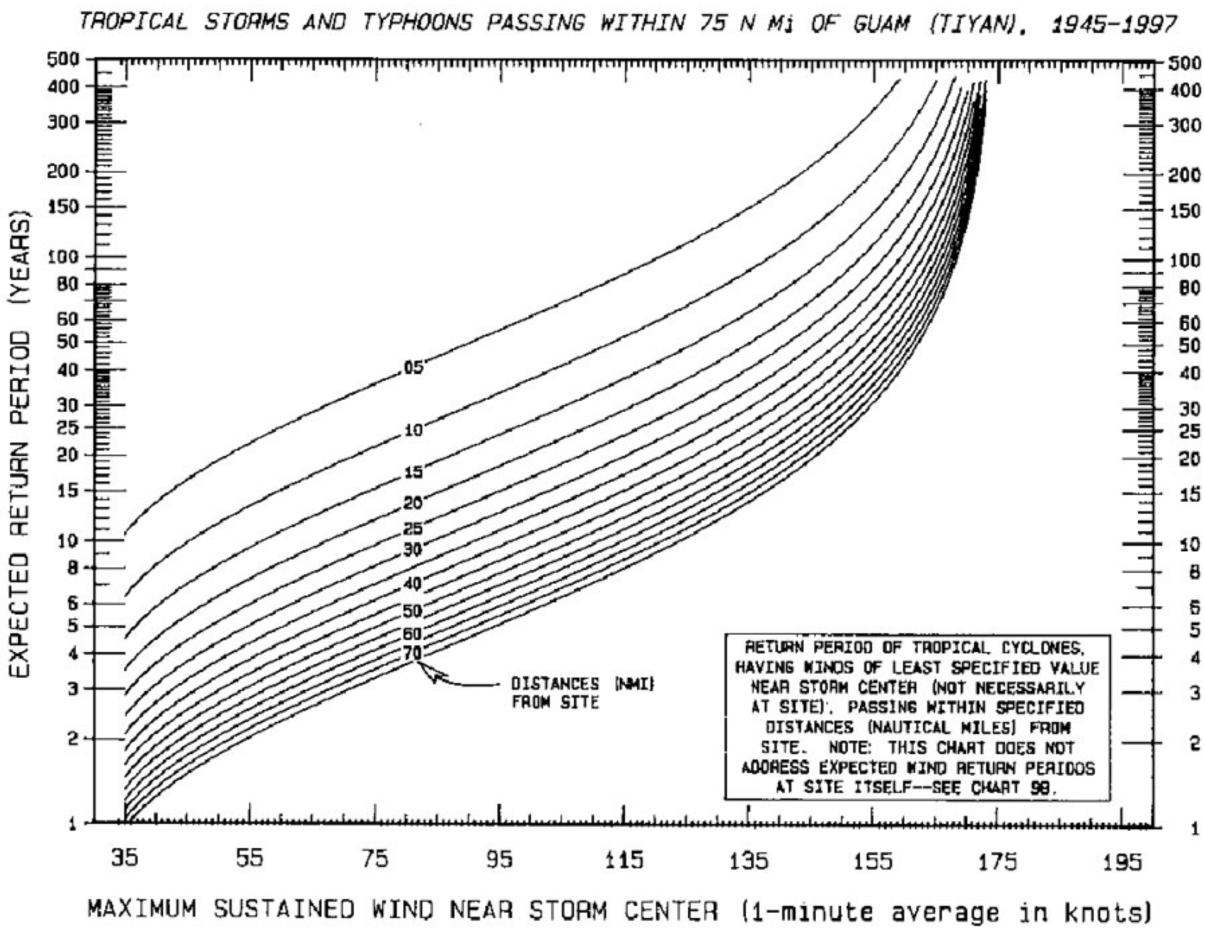

TROPICAL STORMS AND TYPHOONS PASSING WITHIN 75 N Mi OF GUAM (TIYAN), 1945-1997
EXPECTED RETURN PERIOD (YEARS)
MAXIMUM SUSTAINED WIND NEAR STORM CENTER (1-minute average in knots)
05
10
15
20
25
30
40
50
60
70
DISTANCES (NMI) FROM SITE
RETURN PERIOD OF TROPICAL CYCLONES, HAVING WINDS OF LEAST SPECIFIED VALUE NEAR STORM CENTER (NOT NECESSARILY AT SITE), PASSING WITHIN SPECIFIED DISTANCES (NAUTICAL MILES) FROM SITE. NOTE: THIS CHART DOES NOT ADDRESS EXPECTED WIND RETURN PERIODS AT SITE ITSELF--SEE CHART 9B.

CHART 9A

HURISK MODEL: RETURN PERIODS OF SPECIFIED TROPICAL CYCLONE WINDS BASED ON PERIOD OF RECORD, 1945 - 1997. SITES ARE NORTH GUAM (————) AND SOUTH GUAM (- - - - -).

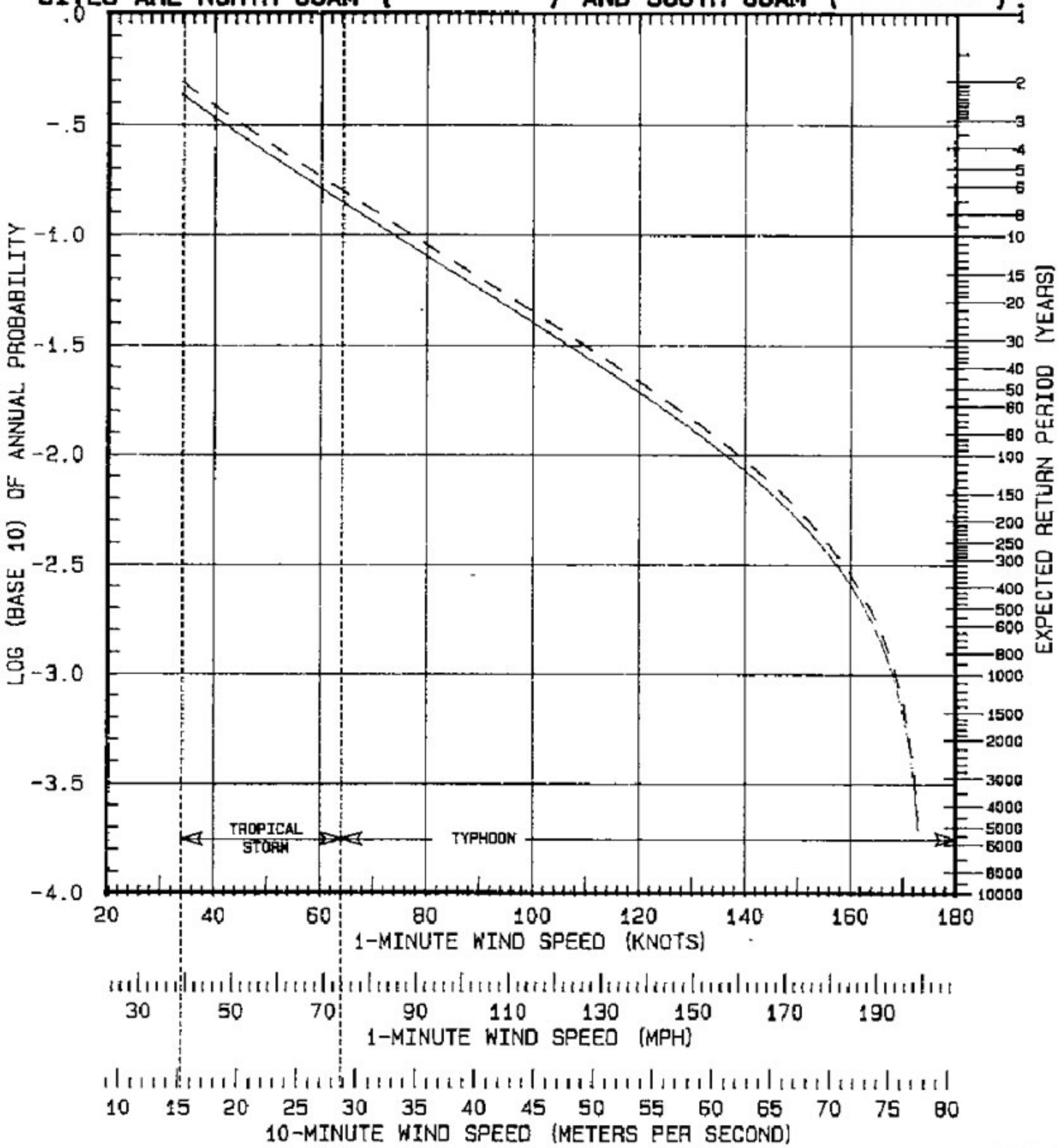
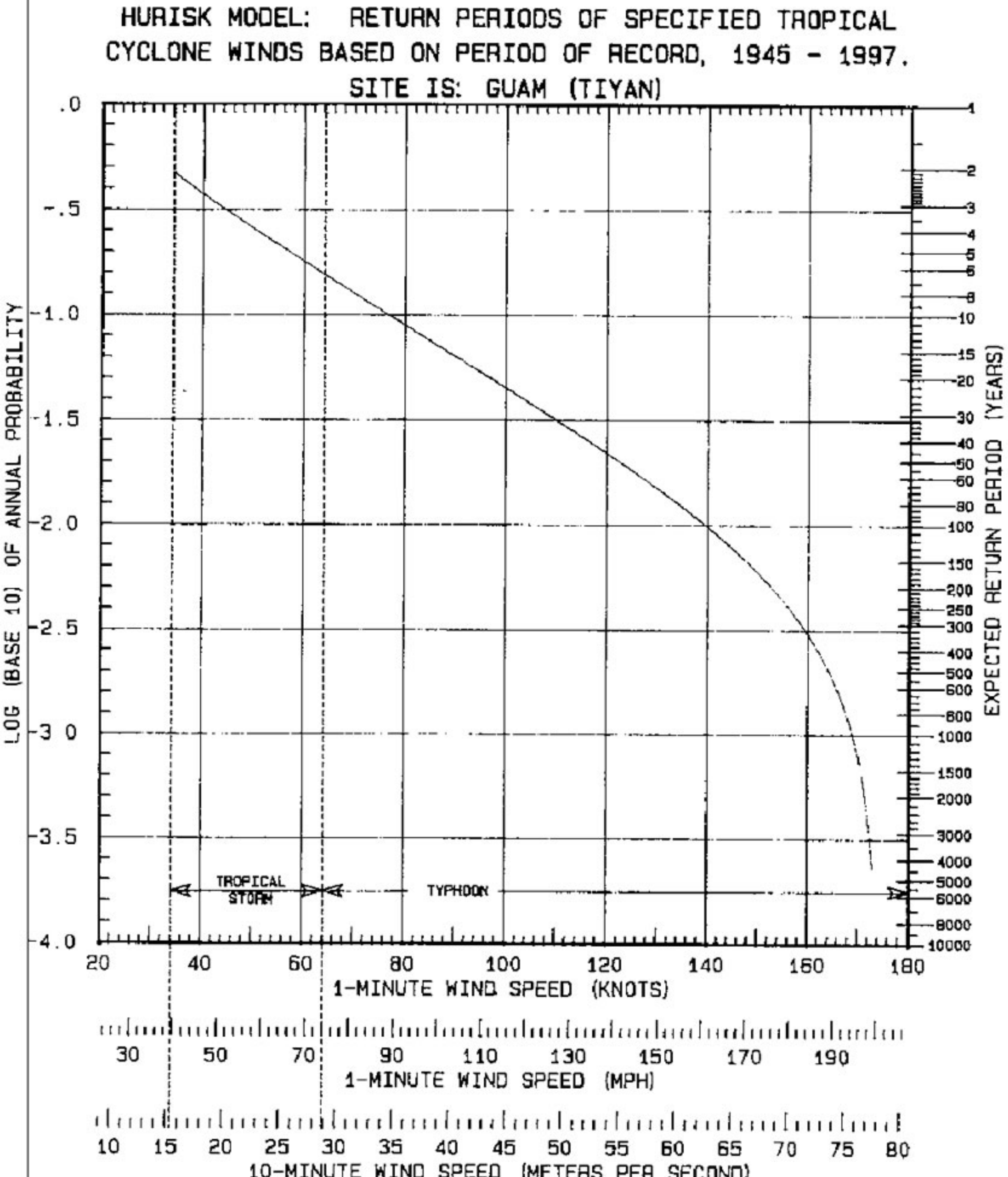


CHART 9B



HURISK MODEL: RETURN PERIODS OF SPECIFIED TROPICAL CYCLONE WINDS BASED ON PERIOD OF RECORD, 1945 - 1997.
SITE IS: GUAM (TIYAN)
LOG (BASE 10) OF ANNUAL PROBABILITY
.0
-.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
EXPECTED RETURN PERIOD (YEARS)
1
2
3
4
5
6
8
10
15
20
30
40
50
60
80
100
150
200
250
300
400
500
600
800
1000
1500
2000
3000
4000
5000
6000
8000
10000
TROPICAL STORM
TYPHOON
20 40 60 80 100 120 140 160 180
1-MINUTE WIND SPEED (KNOTS)
30 50 70 90 110 130 150 170 190
1-MINUTE WIND SPEED (MPH)
10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
10-MINUTE WIND SPEED (METERS PER SECOND)

CHART 9C