up to 45 mph, and rainy conditions and gusty winds from a westerly direction can last for two to three weeks.

The annual average maximum temperature is 86°F and the annual average minimum temperature is 76°F. The annual average high relative humidity (early morning) is 86% and the annual average low relative humidity (late afternoon) is 71%. Table 2.2 illustrates the monthly averages of temperature and relative humidity at Tiyan.

The annual average rainfall varies around the Island, but for Tiyan it is 90.98 inches. The variation in rainfall from year to year can be very large, ranging from a high of 131.97 inches in 1997 (official value, but around 150 inches if Typhoon Paka rainfall is added) to a low of 57.35 inches in 1998. Table 2.2 also shows the mean monthly rainfall, and the highest and lowest observed monthly rainfall values, which are also highly variable. A single event such as a typhoon can account for a high percentage of the rainfall for a given month. April, May, and June are months that transition from the dry to the wet season. Likewise, October, November, and December are months that transition from the wet to the dry season. From year to year, these transition months can be much wetter or much drier than their average rainfall indicates. Tropical depressions, tropical storms, and typhoons can produce very heavy rainfall on the Island. Typhoon Pamela (May 1976) dropped over 30 inches on Guam in two days during May 1976. Thus, May 1976 had about 6 times the normal May precipitation of 6.41 inches. Typhoon Omar in August 1992 dropped over 18 inches in a little over a day.

Rainfall can vary considerably from location to location on the Island, even when the distances between the locations are only a few miles. Figure 2.3 shows the difference in annual rainfall between the Andersen Air Force Base and the NWS Forecast Office at Tiyan (separated by 8 miles).

Table 2.2. Monthly and annual: (a) average maximum and (b) average minimum temperature in degrees F; (c) average maximum and (d) average minimum relative humidity in %; and, (e) average, (f) maximum, (g) minimum rainfall in inches for Tiyan Guam. Length of record is 50 years.

Month	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Jan	85	75	84	69	4.3	18.1	0.9
Feb	85	75	84	67	3.1	13.6	0.3
Mar	86	75	84	65	2.6	9.3	0.4
Apr	87	76	83	66	3.3	15.3	0.4
May	87	77	85	69	5.5	24.1	0.4
Jun	87	77	85	70	5.6	13.3	0.8
Jul	87	76	88	74	9.8	17.7	4.5
Aug	87	76	89	75	13.0	38.8	3.9
Sep	87	76	89	76	13.2	24.3	3.9
Oct	87	76	88	75	12.5	26.5	4.3
Nov	86	77	87	73	8.3	16.1	2.6
Dec	84	76	85	71	5.0	20.0	1.9
Avg Ann.	86	76	86	71	86.2		

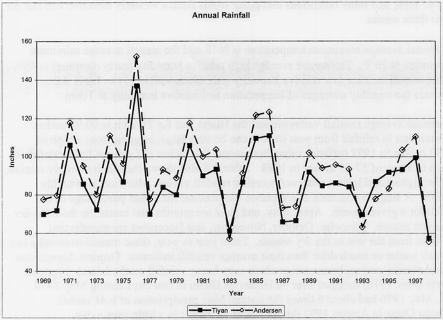


Figure 2.3. Average annual rainfall in inches for the NWS Forecast Office at Tiyan (solid) and for Andersen Air Force Base (AAFB) (open).

2.5.2. Seasonal Wind and Rain Patterns

From December through April, *trade winds* blow persistently from the east-northeast at an average speed of about 15-17 mph. During this period, the weather is relatively dry. In May and June, the winds are from the east at speeds of 10-12 mph. From July through October, the winds veer around to the east-southeast and southeast and weaken to around 5 mph. This is the wet season. However, during these months, the winds can be highly variable in both direction and speed. By November, the winds have come back around to the east and have strengthened to 12-13 mph, and weather conditions become much drier. Figure 2.4 (a), (b) and (c) shows the general low level wind flow during winter months (a), during the summer months (b), and during the transition months of October-November (c), which is also representative of April-May transition season winds.

Figure 2.4 (d) shows the mean monthly position of the near-equatorial or monsoon trough. North of this trough, the winds are from the east, and south of the trough, the winds are from the west. It is in this trough of low pressure that most tropical cyclones are spawned. Occasionally, the monsoon trough becomes very active, causing the westerly winds to strengthen and surge across a large portion of the western North Pacific. This surge can persist for two to three weeks, bringing extended periods of strong westerly winds and heavy rains across the Island.

In June, the trough is south and west of Guam (see Fig. 2.4 (d)). As the season progresses, the trough moves eastward. During July and August, it also moves to the north, and most tropical cyclones during these months strengthen north of Guam. By September, the trough heads back toward the equator, and tropical cyclones begin to develop south and east of Guam, making the Island susceptible to storms that have had several days to develop and intensify. The largest and strongest storms to affect Guam occur in November. However, intense typhoons can affect Guam in April and May, and in the months from July through January.

2.5.2.1 Monsoon Climatology for Guam

Monsoon surges can be classified as weak, moderate, and strong. Each of these types of monsoon surges have different wind strengths, rain intensities, and cloud cover. The characteristics of the three types of monsoon surges are illustrated in Table 2.3.

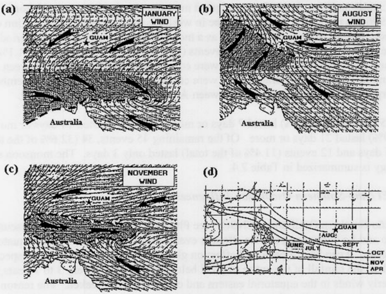


Figure 2.4. Long-term (1900-1979) average surface wind flow across the western Pacific for selected months. (a) January represents the winter season; (b) August represents the summer season; and, (c) November represents winds of the fall and spring transitions. The monsoon trough is indicated by the thick dashed lines. Westerly winds are shaded. Panel (d) shows the monthly mean positions of the monsoon (near-equatorial) trough. (Modified from Lander, 1994)

Table 2.3. General weather characteristics of weak, moderate, and strong monsoon surges.

Characteristic Weather	Monsoon Surge Classification		
Monsoon surge intensity	Weak	Moderate	Strong
Depth of low level westerly winds from surface	~5,000'	~18,000'	~35,000'
Strength of low level westerly winds at surface	< 15 mph	15-30 mph	30-60 mph
General cloud characteristics	Partly cloudy	Overcast; low ceilings when rain occurs	Dense overcast with low ceilings
Waves on the west coast of Guam	4-6'	7-12'	13-30'
Rainfall type	Isolated thunderstorms	Embedded thunderstorms	Heavy squalls Little lightning
Rainfall amount per event	< 1"	< 1.5"	1-2"
Rainfall events per day	1-3	3-6	6-12
Rainfall amount per day	< 2"	2-4"	4-9"

There have been very few studies of the monsoon climatology of the western North Pacific. Lander and Guard (1997) investigated monsoon surges that occurred from 1958 through 1996. In the study, Guam had to be in westerly winds at least some portion of 3 days in order for the event to be classified as a monsoon surge. In the 39 year period, there were a total of 105 events, 74 weak events (70.4%), 22 moderate events (21.1%), and 9 strong events (8.5%). Weak surges were concentrated nearly equally between July, August, and September. Moderate surges were concentrated in August and September. Strong surges were equally distributed between August, September, and October.

Of the 105 events, 51 (48.5%) lasted 7 days or more, 10 (9.5%) lasted 14 days or more, and 2 (1.9%) lasted 21 days or more. Of the remaining 45 events, 34 (32.6% of the total) lasted 4-5 days and 12 events (11.4% of the total) lasted only 3 days. The monsoon surge climatology is summarized in Table 2.4.

2.5.2.2. El Niño-Southern Oscillation Influences

The El Niño-Southern Oscillation (ENSO) (see Philander 1990 for a complete discussion of El Niño and La Niña) is a periodic climatic event, which has its roots in the equatorial Pacific Ocean. It can have a profound effect on global weather patterns, and is especially influential on the rainfall of the entire tropical belt of the Pacific. Every 3 to 7 years, low level easterly winds in the equatorial eastern and central Pacific weaken. The reason for this weakening is not well understood, but may be associated with strong low level westerly winds produced by the development of late-season twin tropical cyclones in the eastern part of the western Pacific. Twins refers to tropical cyclones that develop opposite each other in the Northern and Southern hemispheres. Once the low level easterly winds along the equator weaken sufficiently, warm waters in the western Pacific begin to move to the east into the central and eastern Pacific, warming the sea surface temperatures there. This redistribution of ocean water temperatures alters the distribution of pressure and wind patterns along the equator and in the Southern Hemisphere (Southern Oscillation). In response, clouds and rain shift from the western Pacific to the eastern Pacific. During the El Niño year, Guam and Micronesia are wetter than normal as equatorial and monsoon westerly wind become very strong. By late fall of the El Niño year (e.g., Oct 1997), the equatorial westerly winds propagate to the central and eastern

Table 2.4. Monsoon surge climatology for Guam for the period 1958-1996.

	Apr-Jun	Jul	Aug	Sep	Oct	Nov-Dec	Total	%	#/100 yr
OCCURRENCES									
WEAK SURGE	4	19	19	21	8	3	74	70.4	157
MODERATE SURGE	1	3	6	8	2	2	22	21.1	49
STRONG SURGE			3	3	3		9	8.5	19
TOTAL	5	22	28	32	13	5	105	100	
% OF TOTAL	5.0	20.9	26.7	30.4	12.4	4.8		101	
Number/100 Years	10	46	58	67	27	10		100	
DURATION (days)									
only 3							12	11.4	26
only 4							18	17.4	38
only 5							16	15.2	34
only 6							8	7.5	17
7 or more							51	48.5	109
14 or more							10	9.5	21
21 or more							2	1.9	4

Source: Lander and Guard 1997.

Pacific, and conditions begin to get dry in Micronesia. This shift in the westerly winds and cloudiness allows tropical cyclones to develop in the Central Pacific south of Hawaii in the Northern Hemisphere, and north of Samoa and Tahiti in the Southern Hemisphere. The storms developing south of Hawaii can affect the Marshall Island and the Mariana Islands. Typhoon Paka (Dec 1997) is an example of a tropical cyclone that developed southwest of Hawaii, moved through the Marshall Islands, and hit Guam.

During the year following a strong El Niño (e.g., 1998), conditions in Micronesia become extremely dry. This occurs as the sea surface temperatures off the South America coast and in the equatorial central Pacific begin to return to normal. Rainfall may be less than 20% of normal values for several months at some Micronesian islands. For Guam, rainfall may be 60% below normal for as long as 6 months. During the year following El Niño, tropical cyclone activity is shifted to the west of Micronesia, and the monsoon only rarely surges as far east as the Mariana Islands. This extends the drought into summer.

Occasionally, the sea surface temperatures off the South America coast and in the equatorial central Pacific become colder than normal, and a La Niña event occurs. The La Niña strengthens the equatorial low level easterly winds, bringing dry conditions to equatorial regions of the western Pacific. Tropical cyclone and monsoon activity are also forced farther west than normal. The increased trade winds frequently increases the intensity of trade wind disturbances. The spring can thus be normal to somewhat wetter than normal.

As mentioned above, the El Niño also affects the distribution of tropical cyclone activity across the Pacific. Because of the warm sea surface temperatures near the date line, the near-equatorial trough extends eastward into the Marshall Islands. Thus, activity increases in the Marshall Islands and decreases near the Philippines. While the increased activity doesn't necessarily mean that Guam will get hit by more typhoons, it does mean that Guam will be threatened by more typhoons that have had the opportunity to move over long stretches of warm water and intensify. During the year following El Niño, tropical cyclone activity is pushed far to the west, reducing the threat for Guam. If a La Niña (cold event) occurs, springtime tropical cyclone activity is pushed to the west, but by summer tropical cyclone activity usually returns to normal.

2.5.3. Tropical Cyclones

2.5.3.1. General

Tropical cyclone is a general term that includes the family of *tropical depressions*, *tropical storms*, and *hurricanes/typhoons*. Tropical cyclones are low pressure systems on the scale of 120 miles to 1500 miles across that occur over tropical and subtropical oceans, and in which the winds blow counter-clockwise (northern hemisphere) around a center of organized, deep thunderstorms where the strongest winds generally reside. ***Tropical depressions*** have maximum sustained winds in the range **20 mph to 38 mph**; ***tropical storms*** have maximum sustained winds that range from **39 mph to 73 mph**; and ***hurricanes/typhoons*** have maximum sustained winds that range from **74 mph to about 195 mph**. A special case of the typhoon is the ***super typhoon*** in which the maximum sustained wind ranges from **150 mph to about 195 mph**.

2.5.3.2. Characteristics

Some of the tropical cyclone characteristics are briefly discussed below. They are discussed in greater detail in Chapter 3, Hazards Assessment of Tropical Cyclones Affecting Guam.

2.5.3.2.1. Wind

Wind is the most destructive part of a tropical cyclone for Guam. Storm surge is less of a threat because of the protective nature of the coral reefs, the low number of people that live near the coastline, and the general ease with which the coastal population can be evacuated. Tropical cyclone sustained winds can range on the low end from about 20 mph to nearly 195 mph on the high end. Wind gusts can range from about 25 mph to 245 mph.

Figure 2.5 shows a portion of a wind recording from Tiyan (formerly Naval Air Station Agana) during Typhoon Omar (Aug 1992). The wind is composed of gusts which modulate over a period of 2-3 seconds from peaks (high points) to lulls (low points). The highest peak observed during a specified period of time is the *peak gust* for that period of time. The wind speed averaged over a 1-minute period of the peaks and lulls is the sustained wind. **The sustained wind is approximately 75-80% of the peak gust observed during the averaging period (Krayer and Marshall 1992).**

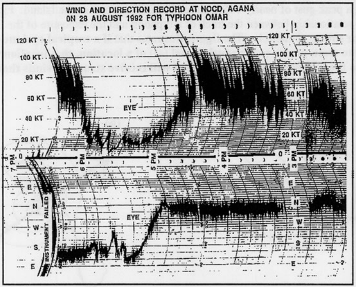


Figure 2.5. A portion of the wind recording at Tiyan (former Naval Air Station) from 2 PM to 7 PM, 28 August 1992. Upper half of the diagram is wind speed in knots; lower half is wind direction.

The peak gust is considered the most reliable piece of information from which to determine the maximum intensity, because the potential peak gust is the same over land and over the open ocean. The magnitude of the difference between the peak and the lull of the gusts produces pressure forces that are particularly destructive to wooden and sheet metal roofs, roofing tiles, windows, and doors. The rapid change in pressure due to the difference between the peaks and lulls of gusts also make your ears "pop" during typhoons, especially intense ones.

In the northern hemisphere, tropical cyclone near-surface winds rotate counter-clockwise around the center. If the tropical cyclone has little movement, the wind field around it is relatively symmetric. If, however, it is in motion, the speed of the movement, also known as translation speed, is added to the right side of the storm with respect to its motion. Likewise, the speed of motion is subtracted from the left side. This creates an asymmetric wind field with the strongest or "dangerous semicircle" to the right side of the direction of motion. **The dangerous semicircle has stronger winds and the destructive winds extend farther from the center.**

This can be illustrated by looking at two typhoons with comparable intensity and translation speed that passed roughly the same distance from Guam, one north of the Island and one south of the Island. Typhoon Roy (Jan 1988) passed about 25 miles north of Guam, exposing the Island to the weaker semicircle and producing a peak gust of about 115 mph on the northern part of the Island. Typhoon Russ (Dec 1990) passed about 25 miles south of the Island, exposing Guam to the "dangerous semicircle" and producing a peak gust of nearly 145 mph on the southern part of the Island. Figure 2.6 shows the relationship between the track of a typhoon and the exposure of the Island to the weak or strong semicircle. The figure illustrates that **if a tropical cyclone moving from east to west, passes to the south** (panel (a)) **of a location, that location will be exposed to the "dangerous semicircle" and will receive stronger winds than if the**

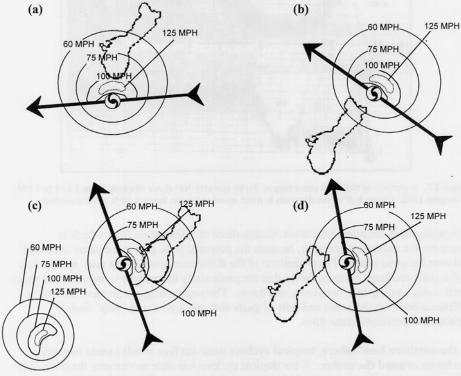


Figure 2.6. The relationship between the position of a storm and the relative strength of the winds that affect the Island. Panel (a) indicates the storm track passing south of the Island--stronger winds affect Island; (b) storm track passes north--weaker winds affect Island; (c) storm track passes west--stronger winds affect Island; and, (d) storm track passes east--weaker winds affect Island.

Table 2.7 shows that the median 48- and 72-hour forecast errors have continued to improve over the last 5 years.

Even initial intensity estimates from satellite data can be as much as 40 mph (35 kt) off. Similarly, there are errors associated with tropical cyclone intensity forecasts. The average intensity forecast errors at 24-, 48- and 72-hour forecast periods hover around 13 mph (11 kt), 18 mph (16 kt), and 26 mph (22 kt). While these errors are generally small, they can occasionally be very large, exceeding 46 mph (40 kt), 69 mph (60 kt), and 92 mph (80 kt), at the respective periods. Typhoons can intensify at rates more than twice the normal rate. This process of **rapid intensification** is often difficult to predict, and often results in these large forecast errors. **Because of these errors, it is wise to prepare for a storm one intensity Category higher than the intensity predicted at landfall or at closest passage.** Thus, the population should prepare for a 60 mph tropical storm (Category B tropical storm) as though it were a Category 1 typhoon.

Table 2.7. Average Joint Typhoon Warning Center (JTWC) mean and (median) track forecast errors for 12-, 24-, 36-, 48-, and 72-hr forecast periods (where available) from 1988 to 1998. 5-year and 10-year average (mean) and median errors are also shown.

Year	Average Forecast Errors (nautical miles)				
	12-hr	24-hr	36-hr	48-hr	72-hr
	Mean (Median)	Mean (Median)	Mean (Median)	Mean (Median)	Mean (Median)
1997	NA	93	NA	164	247
1996	64 (49)	105 (85)	144 (120)	178 (145)	272 (222)
1995	72 (59)	123 (104)	168 (152)	215 (183)	324 (261)
1994	57 (48)	98 (85)	139 (123)	176 (158)	242 (218)
1993	66 (54)	112 (97)	161 (142)	212 (179)	321 (267)
1992	61 (51)	107 (93)	160 (143)	205 (182)	305 (265)
1991	NA	96 (85)	NA	185 (162)	287 (254)
1990	NA	103 (94)	NA	203 (189)	310 (286)
1989	NA	120 (103)	NA	231 (203)	350 (307)
1988	NA	114 (113)	NA	216 (212)	315 (309)
5-Year	64 (52)	106 (93)	154 (136)	189 (169)	281 (247)
10-Year	NA	107 (95)	NA	199 (179)	297 (265)

same tropical cyclone passes the same distance to the north (panel (b)). **Likewise, if a storm passes to the west** (panel (c))**, it exposes the location to stronger winds than if it passes to the east** (panel (d)).

2.5.3.2.2. Eye and eyewall

The most destructive part of a tropical cyclone is the wind in the eyewall. The eyewall is the ring of deep thunderstorm-like clouds that surrounds the relatively calm eye, and contains the maximum winds in a typhoon. An eye begins to form when a tropical storm has sustained winds of about 60 mph, which is also the wind speed that is first classified as "destructive". Only when the eye or the dangerous semicircle of the eyewall passes over a location, has that location experienced the strongest wind of the typhoon for that time period. While Typhoon Yuri (Nov 1991) was a super typhoon, the center of the eye missed the Island by more than 80 miles. Thus, while sustained winds 50-60 miles south of the island were 170 mph (intensity Category 5 winds), those over southern Guam were only 115 mph (Typhoon Category 3 winds).

There are several reasons why an eye passage produces the greatest possible destruction from a typhoon: (i) It contains the region of the typhoon with the maximum winds and most active wind gusts. (ii) Since the eye is generally circular and at the center of the circulation, the eye has the maximum diameter of the circulation, and thus, it exposes a location to nearly the maximum duration of the strongest winds. (iii) As the eye moves across a location, the winds rapidly change in direction, exposing structures to much greater twisting forces than winds that come from the same direction or that change direction slowly. What is loosened by winds from one direction, is frequently dislodged or blown down by winds from the opposite direction.

2.5.3.2.3. Wind measurement

While winds can be measured to the nearest mile per hour and while warnings reflect winds to the nearest 5 knots (6 mph), it is not realistic to expect the winds at a specific location to perfectly match the warning, even if the warning were perfect. First of all, **winds in the warning reflect the average wind over water.** But the winds within a typhoon are pulsating, responding to a multitude of large and small scale forces, which themselves cannot be perfectly measured or accurately predicted. The result is a system with frequently changing wind speeds and wind patterns. Thus, a specific location may not experience the average over-water wind, but one of the stronger or weaker components that make up that average. Winds experienced at a location over land are also heavily modified by terrain and depend to a large part on the exposure of the location.

2.5.3.2.4. Terrain effects and location exposure

Over-water winds can be modified considerably by the terrain, and winds at a specific, over-land location can be quite different from those over water. First the roughness of the surface tends to slow down the wind through the effects of friction. Thus, winds will be greater over grassy terrain than over heavily wooded terrain. Winds will also generally be stronger over flat land than over hilly land. But, the exposure of a location with respect to the terrain and the direction of the wind can have a profound effect on the winds experienced. This is explained in further detail in Chapter 3, Section 3.3.1.

2.5.3.2.5. Minimum central pressure in the eye

Statistically, there is a good relationship between the minimum sea level pressure in the eye/center of a tropical cyclone and its maximum winds. This relationship is often used to derive the maximum winds when the pressure is accurately measured and corrected to sea level. Table 2.5 shows the relationship among satellite current intensity value (CI) (assessed from satellite imagery using the Dvorak wind estimation technique (Dvorak 1977, 1984), minimum pressure, maximum wind, and tropical cyclone wind strength category commonly used in the western North Pacific. However, numerous factors effect the relationship between maximum wind and minimum pressure values (Callaghan and Smith 1998). Thus, only trained meteorologists should derive winds from pressure.

Table 2.5. The relationship between satellite Current Intensity (CI) value, minimum observed central surface pressure (MSLP) in millibars corrected to sea level, and the maximum sustained winds and peak gusts (Max Wind) for western North Pacific tropical cyclones. Tropical cyclone wind strength Categories are also shown. Wind speeds are rounded off to the nearest 5 knots. Pressures are derived from the Atkinson-Holliday (A&H) wind-pressure relationship (A&H 1977).

CI number	MSLP (millibars)	Max Wind (mph)	Tropical Cyclone Wind Strength Category
0.0	>1000	<30G40	
0.5-1.5	>1000	30G40	
2.0	1000	35G45	Tropical Storm A
2.5	997	40G50	Tropical Storm A
3.0	991	50G60	Tropical Storm B
3.5	984	65G80	Tropical Storm B
4.0	976	75G90	Typhoon 1
4.5	966	90G105	Typhoon 1
5.0	954	105G130	Typhoon 2
5.5	941	120G145	Typhoon 3
6.0	927	130G160	Typhoon 3
6.5	914	145G185	Typhoon 4
7.0	898	160G195	Typhoon 5
7.5	879	180G220	Typhoon 5
8.0	858	195G240	Typhoon 5

2.5.3.2.6. Tropical cyclone size

Tropical cyclones come in many sizes ranging from less than 120 miles across (midgets) to over 1500 miles across (giants). Table 2.6 shows the size criterion for the different sizes of tropical cyclones. The midget cyclone is a category in which the relationship between maximum wind and minimum central pressure shown in Table 2.5 does not apply. Midget tropical cyclones can sustain much more wind than their central pressures would support. **Size and intensity are not necessarily related. There are small, very intense typhoons and large, relatively weak typhoons. However, larger storms can miss a location by a large distance and still produce destructive winds, whereas, a very small storm must make a pretty direct hit to cause significant damage. Where a small, intense typhoon does make a direct hit, the destruction can be devastating.**

Table 2.6. Tropical cyclones ranked by size. Ranking scheme is modified from a scheme used by the Japan Meteorological Agency (modified from JMA 1990).

SIZE CLASSIFICATION RANKING	DIAMETER OF 34 MPH CIRCLE (miles)
Midget	< 120
Very small	121-240
Small	241- < 400
Medium	401- < 600
Large	601- 1000
Giant	> 1000

2.5.3.2.6. Tropical cyclone climatology

The tropical cyclone climatology for Guam is discussed in Chapter 4, Risk Assessment.

2.5.3.2.7. Tropical cyclone forecast errors

Although the Joint Typhoon Warning Center (JTWC) is among the best tropical cyclone warning centers in the world, warnings issued by the Center are not perfect. Virtually every tropical cyclone forecast, both track forecast and intensity forecast, has a certain amount of error associated with it. The error is defined as the difference between the location at which a tropical cyclone was predicted to be at a certain time and the position at which it was actually located at that specific time.

When locating tropical cyclones with satellite, errors may range from over 115 miles (100 n mi) for poorly organized, weak tropical depressions to only a few miles for well-organized typhoons with a visible, discernible eye. The average positioning error for tropical cyclones of all intensities is about 28 miles (24 n mi). The median value is 21 miles (18 n mi), meaning that one-half of the position estimates are above that value and one-half are below that value. In general, track forecast errors for Guam are less than those indicated in Table 2.7.

Table 2.7 shows the mean (average) and median track forecast errors for 12-, 24-, 36-, 48-, and 72-hour track forecasts for the last 10 years. The average errors over the last 5 years for the respective periods are approximately 75 miles (65 n mi), 127 miles (110 n mi), 184 miles (160 n mi), 230 miles (200 n mi), and 345 miles (300 n mi). There has been considerable improvement in the 24-, 48-, and 72-hour track forecast errors over the past 20 years, but the rate of improvement has slowed down over the last 5 years.

3. TROPICAL CYCLONE HAZARDS ASSESSMENT

3.1. GENERAL

There are several hazards associated with tropical cyclones. These hazards affect a small tropical island differently than they affect a continental coastal area. In continental areas, only part of the country is affected, while life goes on in the rest of the country. On a small island, the entire population is affected, not only by being hit by an actual tropical cyclone, but even by the threat of being hit by a tropical cyclone. In a continental area, coastal residents can evacuate hundreds of miles inland to evade the wrath of a typhoon/hurricane, but on a small island, evacuation distances are generally only a few miles or less. It is not practical to leave the island. When a continental coastal area is damaged or devastated, outside assistance, equipment, and supplies can arrive as soon as the winds begin to abate. Trucks, buses, and vehicles can deliver large amounts of assistance and supplies. On a small, isolated island, outside assistance, equipment, and supplies must be flown in or must come in by ship. This requires that the airport, including its navigational aids, and the seaport facilities must be sufficiently operational to support the incoming aircraft and ships.

There are some benefits to being on the small island. The area of damage is limited by the size of the island. For example, on Guam, no matter how intense a typhoon is, it can only destroy a total of 212 square miles of anything. A typhoon/hurricane making landfall on a continental area can affect two hundred miles of coastline and can project the damaging winds a hundred miles inland. Thus, a single storm could affect 10,000-20,000 square miles. On an island, there is a unified effort to re-establish the infrastructure, to get the schools in session, and to re-instate the main sources of revenue (e.g., tourism, manufacturing, agriculture). While more resources may be available to the continental area for recovery, the recovery process on a small island is more manageable and more focused. Prioritization of recovery tasks is usually easier, because the primary needs are more evident and they benefit more of the total population. On Guam, the immediate influx of Federal assistance plays an important role in partially off-setting the immediate loss of tourism. Assistance in the form of funding, debris clearance, and increased construction, helps offset a reduction in visitors and an increase in job layoffs.

Guam, to one extent or another, is susceptible to most typhoon-related hazards. However, there are three primary hazards that affect a significantly large part of the population, and that can cause widespread and immediate damage. These are destructive winds, storm surge, high waves, and flooding. There are additional hazards that are dangerous and costly, but they generally are of less concern or affect fewer people. It is important that emergency managers have a good understanding of the hazards associated with tropical cyclones and understand their potential impacts. These hazards are listed below and are discussed in subsequent sections of this Chapter. The hazards are:

(1) *destructive winds and wind-blown debris*;

(2) *storm surge*, *high waves*, and *inundation*;
(3) *torrential rains* and *flooding*;
(4) *wind shear* and *mechanical turbulence*;
(5) *rough seas* and *hazardous surf*;
(6) *tornadoes*;
(7) *sea salt deposition*;
(8) *erosion* and *pollution*; and,
(9) *slope failures*.

3.2. GENERAL TROPICAL CYCLONE CHARACTERISTICS

3.2.1. Classification of tropical cyclones

The term *tropical cyclone* (TC) is the generic term that includes *tropical depression*, *tropical storm*, *typhoon*, and *super typhoon*. Tropical cyclones are classified according to their intensity and level of organization. The intensity of a tropical cyclone is typically described in two primary ways: (1) the highest sustained one-minute over-water wind speed (at 33 feet above the surface) at the *radius of maximum winds* (RMW), and (2) by the *minimum sea level pressure* (MSLP) in the eye or center. The highest wind speed and MSLP are related, and there are several wind-pressure relationships for tropical cyclones. The Joint Typhoon Warning Center (JTWC) uses a tropical cyclone wind-pressure relationship developed by Atkinson and Holliday (1977). In the real world, there is considerable variation in the observed MSLP and the observed *maximum sustained wind*, and for this reason we opt to use the wind parameter as the measure of intensity. The following classifications pertain to the various intensities of *tropical cyclones*:

(1) *tropical depression (TD)* -- a tropical cyclone with maximum sustained 1-minute mean surface winds of 33 kt (38 mph). This implies that a *TD* has no lower limit. The *TD* must have a closed circulation. In practice, the Joint Typhoon Warning Center issues warnings when the circulation reaches 25 kt (29 mph).

(2) *tropical storm (TS)* -- a tropical cyclone with maximum sustained 1-minute mean surface winds in the range of 34 to 63 kt (39 to 73 mph).

(3) *typhoon (hurricane) (TY)* -- a tropical cyclone with maximum sustained 1-minute mean surface winds of 64 to 129 kt (74 to 148 mph). West of the international date line these systems are called typhoons and east of the date line they are called hurricanes.

(4) *super typhoon (STY)* -- a typhoon with maximum sustained 1-minute mean surface winds of 130 kt (150 mph) or greater. While this implies no upper limit of wind speed, in reality, there is an upper limit of around 165-170 kt (190-196 mph).

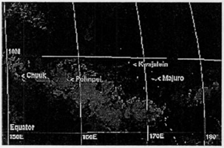
When a tropical cyclone in the western North Pacific attains the intensity of *TD*, it is given a number followed by "W" (e.g., TD 21W, etc.), and when it reaches *TS* intensity, it is given a name (e.g., TS Orchid, TY Bill, etc.). The numbers are given sequentially beginning with the first *TC* of the year and ending with the last *TC* of the year. JTWC issues the TC names. A list of the names is given in Appendix A. Occasionally, the names of deadly or destructive storms are retired, and the list changes. These lists should be updated annually from the NWS Office at Tiyan.

The precursor to a *tropical depression* is a *tropical disturbance*. A *tropical disturbance* is a discrete system of apparently organized convection (deep clouds and thunderstorms), generally 100 to 300 n mi in diameter, organizing in the tropics or subtropics, and having maintained its identity for 12 to 24 hours. While there are many *tropical disturbances* during the year, only a few develop into *tropical cyclones*.

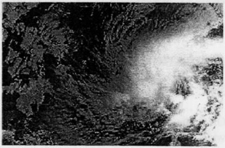
3.2.2. Cloud and wind structure of tropical cyclones

The cloud structure of *tropical cyclones* (*TC*) is highly variable, but to the trained eye, specific characteristics stand out that allow an analyst to locate the center and estimate the wind speed of the TC with credible accuracy. The Dvorak tropical cyclone satellite intensity estimation technique (Dvorak 1977, 1984) is the standard method used around the world to determine TC intensity from satellite data. Figure 3.1 illustrates the cloud structure of a "typical" (a) tropical disturbance, (b) tropical depression, (c) monsoon depression, (d) weak tropical storm, (e) severe tropical storm, (f) typhoon without a visible eye, (g) typhoon with a visible eye, and (h) super typhoon.

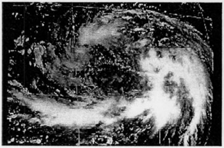
(a tropical disturbance



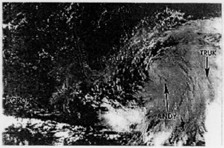
(b tropical depression



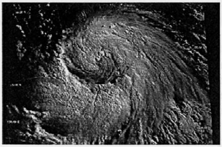
(c monsoon depression



(d weak tropical storm

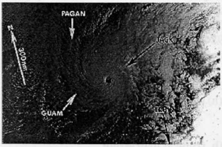


(e severe tropical storm



(f typhoon without visible eye

(g typhoon with visible eye



(h super typhoon

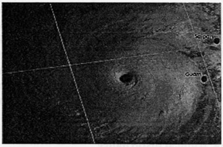


Figure 3.1. Satellite imagery of a "typical" (a) tropical disturbance, (b) tropical depression, (c) monsoon depression, (d) weak tropical storm, (e) severe tropical storm, (f) typhoon without visible eye, (g) typhoon with visible eye, and (h) super typhoon.

3.3. DESTRUCTIVE WINDS

3.3.1. Wind characteristics

On Guam, the most damaging part of a tropical cyclone of at least typhoon intensity is the wind. The wind and its effects are somewhat complex, but a knowledge of the behavior of wind is important in understanding actual and potential wind damage. Wind is the transport of air across a location. This transport or movement of air often appears to be smooth or laminar, but in reality, the motion of the air is quite turbulent. The turbulence, which disrupts the smooth horizontal flow of air by introducing vertical motions to the air, results from a number of factors. Changes in the roughness of the surface over which the wind passes causes turbulence. Elevation and shape of the terrain causes turbulence. The introduction of air with different momentum, such as is observed when a thunderstorm passes, causes turbulence. And, differences in heating of the surface over which the air passes causes turbulence.

The wind reflects this turbulence in the form of *peaks* and *lulls* in the wind speed. The frequency of occurrence and the differences in magnitude between the *peaks* and the *lulls* of the wind speed is referred to as the *gustiness* of the wind. The *peaks* and *lulls*—the *gustiness*—of the wind can be seen quite vividly by looking at a recording of the wind measured by an anemometer that can detect changes in the wind speed each second. When winds get strong, the *gustiness* is accentuated, especially by changes in the downward transport of momentum by deep convective clouds. Figure 3.2 shows the character of the wind during Typhoon Paka (December 1997). Several characteristics can be seen from the recording. The *peak gust* is the highest 1-3 second wind observed in a tropical cyclone. In general, the wind gets gustier as the wind speed increases. The strongest wind is located beneath the eye wall cloud, just outside the eye (between 19 and 23 on the horizontal (time) scale). Winds inside the eye are relatively calm. The strong winds associated with the eye wall cloud fall off abruptly at the leading edge of the eye and pick up abruptly at the trailing edge of the eye. The wind direction changes nearly 180 degrees with the eye passage.

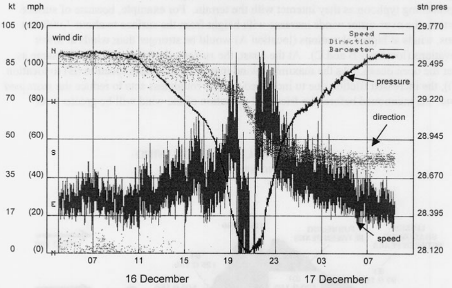


Figure 3.2. The wind speed and surface pressure record of Typhoon Paka (Dec 97) at Kuentos Communications, Inc., Maite, Guam. (Kuentos web page)

The intensity of tropical cyclones is given as a *sustained wind*, which is the highest value of the wind averaged over a 1-minute period. Over water, the *maximum sustained wind* is about 78 percent of the *peak gust* (Krayer and Marshall 1992). For example, if the peak gust were 100 mph, the sustained wind would be 78-80 mph. Friction at the Earth's surface causes the wind to slow down as the wind gets closer and closer to the surface. **The friction over land is generally greater than that over water, and thus, the**

slowing of the wind is greater over land than over water. Friction also increases with the roughness of the terrain, so on Guam, the more mountainous terrain to the south will accentuate the frictional slowing of the wind more than the flatter terrain to the north. Figure 3.3 illustrates how the *sustained wind* over water changes over land (see Chapter 2, Section 2.5.3.2.4.). It should be noted that the *peak gust* over land and over water are virtually the same. This is because it is the deep convective clouds (thunderstorms) that transport the maximum winds in the tropical cyclone (usually at the 3,000-4,000 foot level) down to the water and the land surfaces. There is very little loss of momentum by this process, and **friction does not appear to significantly affect the maximum value of the peak 1-3 second gust differently over land than over water. The greater turbulence over land does, however, affect the frequency that the *peak gust* actually makes it down to the surface. Thus, the peak gust will likely be observed more frequently over water than over land and more frequently over smooth terrain than over rough terrain.**

Figure 3.3 illustrates the various modifications that might occur on the winds of an approaching typhoon as they interact with the terrain. For example, because of surface friction, the over-water winds increase with height from the surface to about 3,000 feet Thus, winds at higher elevations (location A) would be stronger than winds at lower elevations (locations B and C). At the coast, the *sustained wind* is virtually the same as over the open ocean. . As the maximum wind moves inland (from location (B) to location (C)), the increased friction due to increased surface roughness acts to reduce the *sustained wind*. As mentioned before, the frictional reduction of the wind will be greater over

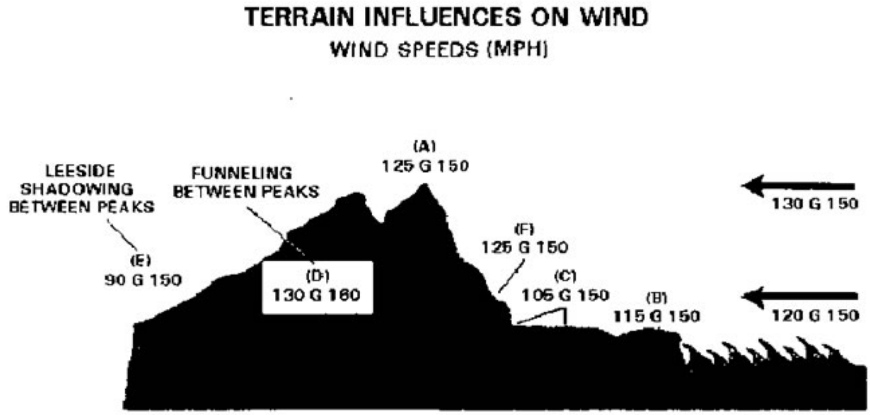


Figure 3.3. Friction- and terrain-induced modifications to the over-water *sustained wind speed* and *gusts*. Winds can be interpreted as miles per hour or knots. (A) is a mountain peak; (B) is a near-coastal area; (C) is an inland plateau area; (D) is a narrow valley between peaks; (E) is a protected or shadowed exposure; and, (F) is a higher elevation with direct exposure to the wind. (From Guard 1995)

rough terrain than over smooth terrain. Also, winds that get funneled down narrow valleys (location D) or between tall buildings can be much stronger than those over open terrain (locations B and C). This *Venturi effect* gives the perception that the tropical cyclone is stronger than advertised. Mountains/hills (location E) and even buildings and heavy vegetation can block the wind, shadowing a location from the worst effects of the over-water wind. Finally, cliffs/bluffs (location F) can cause the wind to accelerate rapidly up over the cliff/bluff, exposing the cliff line to significantly stronger winds than those initially hitting the lower part of the cliff (location(C)). Thus, for a given over-water wind, a variety of winds can be experienced over land, especially hilly or mountainous land. Winds can also accelerate up and down hillsides, between structures/buildings, and where highways cut through hills. Some areas on Guam have shown especially high vulnerability to these accelerations and are shown in Table 3.1. Despite the modification of the *sustained winds* by land, **the *potential peak gust* over land is virtually the same as that over water**. The *over-water sustained winds* and the corresponding *peak gusts* for tropical cyclone wind speeds in miles per hour and in knots are given in Appendix B. Values are given to the nearest 5-knots to correspond to JTWC warning values.

Table 3.1. Locations on Guam showing high vulnerability to localized accelerations of tropical cyclone-induced winds.

Location	Comments
Asan, Piti	Winds accelerate down Nimitz Hill
Tumon	Winds accelerate between high rise buildings
Harmon	Winds accelerate between large warehouses
Nimitz Hill Flag Circle	Winds accelerate up Nimitz Hill
Route 4, Molojloj to Yona Route 4, vicinity of Umatac	Winds accelerate along the highway where it passes through hills
Road to Terague Beach	Winds accelerate where road cuts through cliff
Valleys in southern mountains	Winds accelerate up and down slopes and around and between peaks
Talofofo Village, Cross Island Road	Winds accelerate through the Ylig River valley and down the backside of Mt Schroeder, Mt Sasalaguan, Mt Lam Lam, Mt Jumullong Manglo
Naval Activities old NSD area	Winds accelerate between large concrete warehouses

3.3.2. Destructive properties of winds

On Guam, *destructive winds* are defined as sustained winds of 60 mph (50 kt) or more. This wind speed has been selected because it is sufficient to knock dead limbs from trees, to blow unattached sheet metal and plywood through the air, and to create extremely hazardous surf and rip tides. It puts people at risk, unsecured planes at risk, and unprepared ships in the harbor at risk.

of rainfall runoff or river water that can't get to the open ocean and, therefore, backs up (SEI 1993).

Storm surge refers to elevated height of sea water that is ahead of and to the right of (in the Northern Hemisphere) the eye of an approaching tropical cyclone. The danger of the *storm surge* is that it can raise the level of water high enough to allow wind-driven waves to push a wall of water inland with such force that it can displace and destroy even multi-story concrete structures. *Storm surge* depends on four primary characteristics of a tropical cyclone: (1) the atmospheric pressure in or near the eye; (2) the intensity of the surface winds; (3) the size of the strong wind field, and (4) the forward speed of motion or *translation* of the tropical cyclone. The pressure at a location represents the weight of the column of air above that location, which pushes down against the location. If the pressure is low as in a tropical cyclone, then the weight of the column of air is less. Thus, the ocean water is compressed less and the height of the ocean rises. The greatest rise occurs where the pressure is lowest, that is, in the center of a tropical cyclone. The relationship between the pressure and the height of the ocean is referred to as the *inverse barometer* effect. Table 3.4 shows the contribution of the sea level rise that occurs only from the lowering of the central pressure in the center/eye of a tropical cyclone. The corresponding wind speed for the given pressure is also shown to provide an idea of the tropical cyclone intensity.

Table 3.4. Contribution of the sea level rise that occurs from the lowering of the central pressure in the center/eye of a tropical cyclone. Corresponding wind speed is determined from the Atkinson-Holliday wind-pressure relationship (Atkinson and Holliday 1977). hPa = hecto-Pascals, mb = millibars, ft = feet, in = inches, mph = miles per hour, and kt = knots.

[illegible]	[illegible]		[illegible]	
[illegible]	(ft)	(in)	[illegible] (mph)	(kt)
1000	0.4	5	34	30
980	1.1	13	68	60
960	1.7	21	95	83
940	2.4	29	117	103
920	3.0	36	138	121
900	3.7	44	158	139
880	4.3	52	177	155
860	5.0	60	195	171

So, due to low pressure, a mound of elevated sea water occurs in the center of the tropical cyclone and extends outward away from the center. That is to say, the *inverse barometer* effect decreases away from the eye/center. The stress created on the sea by the strong winds (which extend from the inside of the eye wall cloud to near the radius of 60 mph winds) pushes this elevated area of water along the strong wind band, producing swells that propagate outward at about 25 mph. The mound of water is maintained most efficiently ahead of and to the right of the direction of motion of the cyclone (Northern Hemisphere), where the swells move more slowly in relation to the storm. There, the

There are several aspects of the wind that cause it to be destructive. **The *force* of the wind represents the effect of the air pushing against an object. The *force* of the wind varies as the square of the wind speed.** This means that if the wind speed is doubled, the destructive potential due to the *force* of the wind is quadrupled. Thus, a 100 mile per hour wind will have at least four times the *force* of a 50 mile per hour wind.

However, the *force* of the wind is not the only destructive effect of the wind. The *gustiness* contributes significantly to the total damage. The larger the difference between the *peak* and the *lull* of the gust, the greater are the pressure differentials imparted on various parts of structures. These differentials impose various degrees of torque (twisting forces) and suction (sucking forces) that are particularly destructive to wood and metal roofs, to windows, to doors, to shingles, and to other parts of structures. For intense typhoons, gusts can even be destructive to doors and windows of concrete structures protected by storm shutters and to the storm shutters themselves. **The ability of these structural parts to cope with the twisting and sucking forces depends largely on their design.** While wind gusts from even the most intense typhoons (strong Typhoon Category 5 intensity) probably won't cause direct structural damage to steel reinforced concrete structures, these winds will likely cause failure of doors, windows, and storm shutters, and they can pick up large objects such as cars and throw them into the concrete structures, causing considerable indirect structural damage.

The gustiness of the wind also lifts roofs, then lets them relax, then lifts them again, eventually pulling up nails and screws. Similarly, the gusts affect sheet metal walls, getting into gaps where the metal sheets join, and eventually pulling them apart. When the effects of gusts are combined with the force of the wind, the destructive effects vary as the cube of the wind speed. Thus, a 100 mile per hour wind will have at least nine times the destructive potential of a 50 mile per hour wind. The effects of the wind forces on the structures of Guam will be discussed in more detail when addressing wind vulnerability in Chapter 6.

3.3.3. Historical maximum winds on Guam

Historically, the extreme winds on Guam have come from a single source—typhoons Despite the existence of several anemometers on the Island, these wind-measuring devices frequently fail during intense typhoons. The most common sources of failure are power outages and damage due to airborne debris. For this reason, the historical record is full of holes and incomplete data, usually during and after an eye wall passage. Table 3.2 lists the strongest tropical cyclone-induced winds observed on the Island since 1923. The strongest measured wind gust—170 mph—occurred during Typhoon Paka (Dec 1997). The strongest wind gust experienced in recent history on the Island is estimated to be about 200 mph during Typhoon Karen (Nov 1962).

3.4. STORM SURGE, WIND-DRIVEN WAVES, AND INUNDATION (Also See Section G—Rough Seas and Surf)

3.4.1. Characteristics of *storm surge* and its causes

Inundation or *wave run-up* refers to the process of the incursion of sea water onto a land area that is normally dry. The amount of damage associated with inundation depends on: (1) the maximum height of the sea water at the coastline and (2) the maximum distance that the sea water penetrates inland. The maximum height of the sea water at the coastline depends on several contributing factors that are shown in Table 3.3. The maximum distance that the water penetrates inland depends on the maximum height of the sea water at the coastline, the elevation characteristics of the terrain, and the amount

Table 3.2. Wind extremes on Guam (1923-1997).

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Paka	Dec 98	149*	170*	Port Ops	30
Pamela	May 76	138	159	Taguac (NWS)	365
Omar	Aug 92	130*	150*	Naval Air Station (Tiyan)	255
Karen	Nov 62	125*	144*	Nimitz Hill	634
No Name	Mar 23	122*	140*	Sumay (MCS)	25
Russ	Dec 90	111	128	Naval Magazine	282
No Name	Nov 40	110*	127*	Agana (Fort Apugan)	182
Allyn	Nov 49	110*	127*	Harmon Field	300
No Name	Aug 41	108	124	Agana (Fort Apugan)	182
Gay	Nov 92	105	121	Naval Air Station (Tiyan)	255
Yuri	Nov 91	100	115	Naval Air Station (Tiyan)	255
Roy	Jan 88	98	113	Andersen AFB	612
Olive	Apr 63	87	100	Nimitz Hill	634
Lola	Nov 57	84*	97*	Naval Air Station (Tiyan)	255
Querida	Sep 46	82	94	Naval Air Station (Tiyan)	255
Brian	Oct 92	80	92	Nimitz Hill	634
Betty	Nov 80	79	91	Naval Air Station (Tiyan)	255
Ora	Nov 68	77	89	Andersen AFB	612
Kim	Nov 77	77	89	Naval Air Station (Tiyan)	255

*** Peak measured wind before anemometer failure.**

Table 3.3. Factors contributing to the maximum height of sea water at the coastline.

[illegible]	[illegible]
Maximum height of storm surge (inverse barometer and wind-stress effects)	Depends on tropical cyclone size, intensity, speed of motion, minimum central pressure
Height of wind-driven waves	Depends on tropical cyclone intensity and size
Height of the astronomical tide	Depends on time of day--2 high and 2 low per day
Coastal morphology—open bay or reef	Bays focus storm surge and wind waves; open bays allow some wave setup; reefs hamper setup
Width of the reef	Wider reefs dampen waves and reduce inundation
Angle that waves approach the coast/reef	Highest waves will be those perpendicular to reef

mound of water is being constantly reinforced by the wind stress (swell generation) and elevated by the inverse barometer effect. This process is shown in Figure 3.4(a). To the rear of the cyclone, the swells propagate away from the strong wind band without reinforcement, and they eventually decay.

Swell decay generally occurs once the swell moves beyond the 35-kt (39 mph) wind band. The rate of decay largely depends on the fetch width, i.e., the width of the strong wind zone. Thus, for TCs passing the same distance from a location, the decay rate for small tropical cyclones is much faster than that for large cyclones of comparable intensity. The decay process is illustrated in Figure 3.5.

When this reinforced mound of water approaches a coast line with a continental shelf (e. g., the US East Coast, the US Gulf Coast, Bangladesh), it produces a *storm surge*. Figure 3.4(b) illustrates the *storm surge* process. As the mound of water approaches the coast line, the sub-surface water feels the frictional effects of the gradually sloping ocean bottom, and the water slows down. The water nearer the surface is affected less by friction, and moves faster, causing the water to pile up. This process is *wave set-up*. Eventually the building wave gets too massive and breaks, pushing the large volume of water toward shore (USACE 1985). The return flow of the water follows the ocean bottom, and is again affected by friction, which causes the return flow to be slower than the inward transport of water by the breaking waves. The result is a further rising of the water level. This is part of the *storm surge*, and it can create considerable inundation. **The height of the *storm surge* is calculated independent of the astronomical tide, but rides on top of it. Thus, the water level will be higher at high tide than at low tide.** Since for Guam, there are two high tides and two low tides during a 24-hour period, there is only 6 hours between a low tide and a high tide. **Because there is uncertainty about the exact location of the maximum height of water ahead of the tropical cyclone and there is error in the prediction of the time of arrival of the tropical cyclone, preparations and evacuation decisions should be based on the assumption that the arrival of the maximum *storm surge* will occur at high tide.**

The *inundation* in coastal areas is not merely determined by the height of the *storm surge* and the height of the astronomical tide. The strong winds associated with the cyclone also produce (wind-driven) waves that ride on top of the storm surge, and the coral reefs that surround most of the Island modify the normal behavior of the *storm surge*. On Guam, it is only the open bays in which rivers drain that remotely resemble the continental shelf areas of the United States, and thus, somewhat mimic the *storm surge* and wind wave behavior seen in the US coastal areas. In the continental shelf areas, the ocean bottom gradually slopes toward shore, allowing the height of the oncoming waves to significantly increase. This *wave setup* can occur to some extent in the open bays, especially in southern and eastern Guam—Umatac Bay counterclockwise to Pago Bay. **The small size and restricted entrances of these bays act to focus and contain the high water, allowing the strong winds to drive the water toward the shore. This is a significant cause of the inundation observed on Guam, and is a frequent occurrence in Inarajan Bay, Talofofo Bay, Ilig Bay, and Pago Bay, when intense tropical**