cyclones pass to the south of the Island. At Pago Bay, water is driven inland over an elevated ridge of land and forms an inland lake. During Typhoon Yuri, the "lake" actually floated several houses off of their cinder block pillar foundations.

3.4.2. Reef geomorphology and the effects of the reef on storm surge and wind-driven waves

The reef affords the Island considerable protection from the ocean. It does this in two ways. Since the reefs rise from deep water, there is no gradually sloping coastline at the reef fringe, and thus, there is little, if any, *wave setup*. Only the water that is higher than the reef, i. e., the water that clears the reef, has the potential to reach the normally dry land. Thus, at high tide, more of the storm surge-generated water will clear the top of the reef than at low tide. The water that does clear the reef is then driven toward shore by the strong winds. The water over the reef is relatively shallow, and thus the reef acts to dampen the waves. **The wider the reef and the shallower the water on top of it, the greater is its dampening effect on incoming waves. Conversely, where the reef is narrow, there is less dampening of the waves, and there is a greater chance that the waves will reach higher levels of the coastline and cause higher levels of *inundation*. Similarly, deeper water over the reef will result in less dampening of the waves and more *inundation* as the water is driven by the wind.**

When waves and swells hit the reef, their maximum energy is transported toward land where the wave/swell direction is perpendicular to the reef. If the wave/swell hits the reef at an angle, only part of the energy is directed toward land and the potential *inundation* is reduced. The greater the angle deviates from the perpendicular, the smaller is the potential for *inundation*. However, the coastline around Guam is very irregular, and while the wave/swell might not be perpendicular to a reef in one location, it could be perpendicular to a location only a short distance away. As a typhoon approaches the Island, small changes in the wave/swell direction can make reef areas vulnerable that earlier weren't vulnerable. It is very difficult to precisely predict exactly where the waves/swells will be perpendicular to the reef, and thus it is prudent to evacuate general coastal areas based on the location of the tropical cyclone with respect to the Island. Figure 3.6 shows the lateral vulnerability of the coastal areas to inundation in relation to the tropical cyclone location and movement in relation to the Island. The vertical vulnerability within this lateral vulnerability zone is dependent upon the height of the incoming swells, the strength of the typhoon winds, the central pressure of the typhoon, and the height of the tide. If the eye passes directly over the Island, then nearly all of the coastal locations become vulnerable, especially near the eye wall where the winds are very strong. Here the swell becomes less of a factor and the wind-driven waves become more of a factor.

The geomorphology of the reef is complex. There are cuts in the reef that normally allow water breaking over the reef to return to the ocean. With more intense tropical cyclones, the force of the incoming water can reduce the normal drainage, causing water to pile up inside the reef. With intense storms, the cut can in fact act as a funnel for the incoming

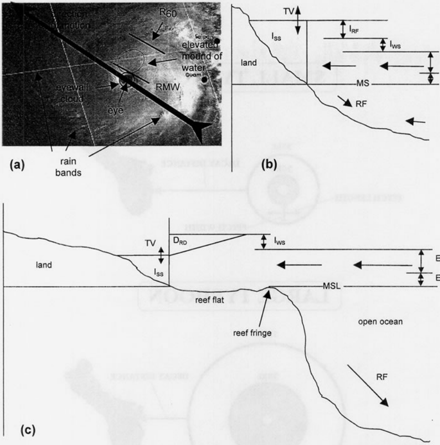


Figure 3.4. Conceptual models of the development of tropical cyclone-induced storm surge and inundation. (a) Diagram showing the elevated mound of water due to wind stress and the inverse barometer effect in relation to the typhoon's eye, eye wall cloud, direction of movement, radius of maximum wind (RMW), and radius of 60 mph winds (R_{60}). (b) Storm surge generation and inundation at coastal areas with a continental shelf. E_{WS} is the storm-induced elevated water level due to wind stress and E_{IR} is the elevated water level due to the inverse barometer effect; I_{WS} is the water level increase due to wave set-up and I_{RF} is the increase in the water due to water pile-up from reduced return flow; I_{SS} is the inundation or storm surge, RF is the return flow, MSL is mean sea level and TV is tidal variation. Shorter arrow lengths indicate slowing due to bottom friction. (c) Inundation at coastal areas with coral reefs. E_{WS} is the storm-induced elevated water level due to wind stress and E_{IR} is the elevated water level due to the inverse barometer effect; I_{WS} is the water level increase due to wave set-up and D_{RD} is the water level decrease due to reef dampening; I_{SS} is inundation, RF is return flow, and MSL is mean sea level.

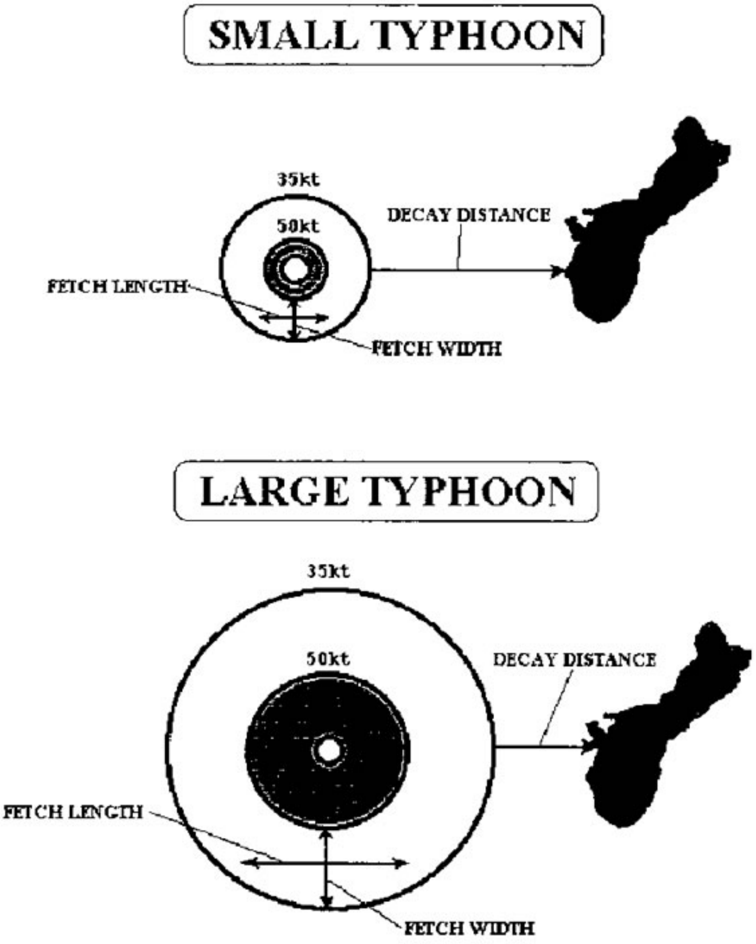


Figure 3.5. Comparison of fetch length, fetch width, and decay distances for large and small tropical cyclones moving the same distance from a given location. (Modified from Lander and Guard 1997)

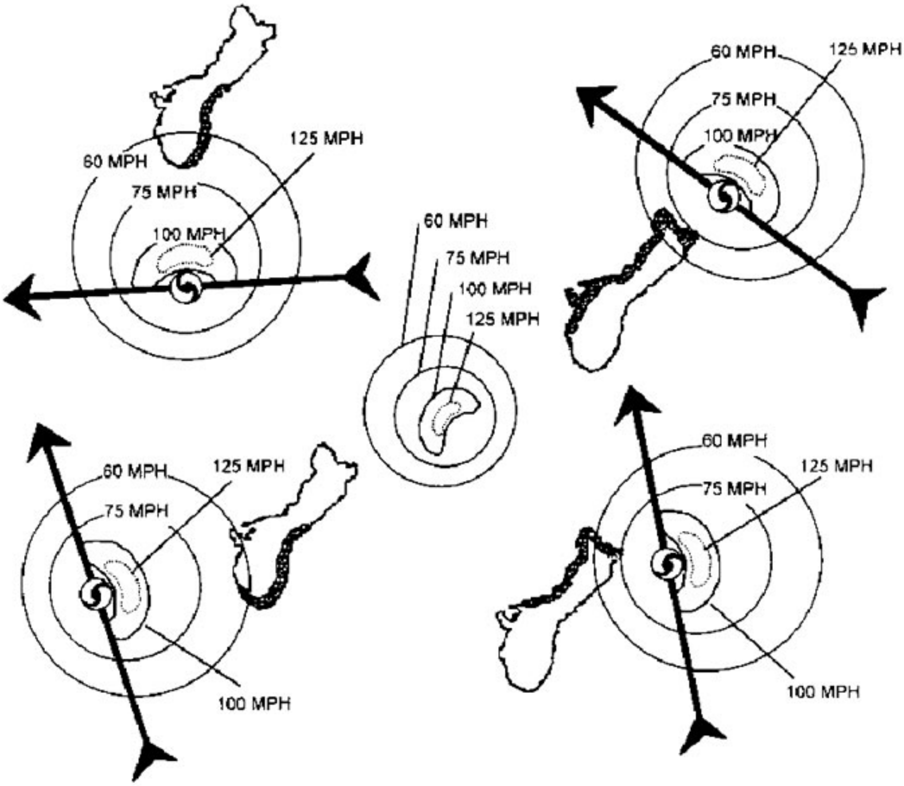


Figure 3.6. Vulnerability of coastal areas to coastal inundation in relation to the tropical cyclone location and movement. The most vulnerable areas are shaded. (Modified from Guard 1995)

water, producing a localized area of higher waves. There are also areas where the reef folds into the coastline, providing large channels that can funnel large amounts of water to shore in the form of very large waves. On Guam, this phenomenon usually occurs near uninhabited cliff lines, but there are a few more accessible areas and inhabited areas where this funneling occurs, most notably at the Inarajan Pools and at Asiga Beach just north of Malojloj on the southeast coast. During Typhoon Yuri, waves as high as 30 feet hit these areas. Figure 3.7 shows some of the features of the reef. Where land is closer to the reef margin, the width of the reef is narrow, and *inundation* is greater than where the reef is wide. Guam's reefs range in width from about 2,500 feet on parts of Tumon Bay, Agana Bay, and Asan Bay to 50 feet where they curve into the coast (USACE 1980).

The expected *storm surge* heights for particular intensities (Categories) of tropical storms and typhoons is summarized in Chapter 5, Section 5.3, The Saffir-Simpson Tropical

Cyclone Scale, and in more detail in Appendix C. Coastal wave action, storm surge, and specific coastal and port damage are discussed in Appendix C.

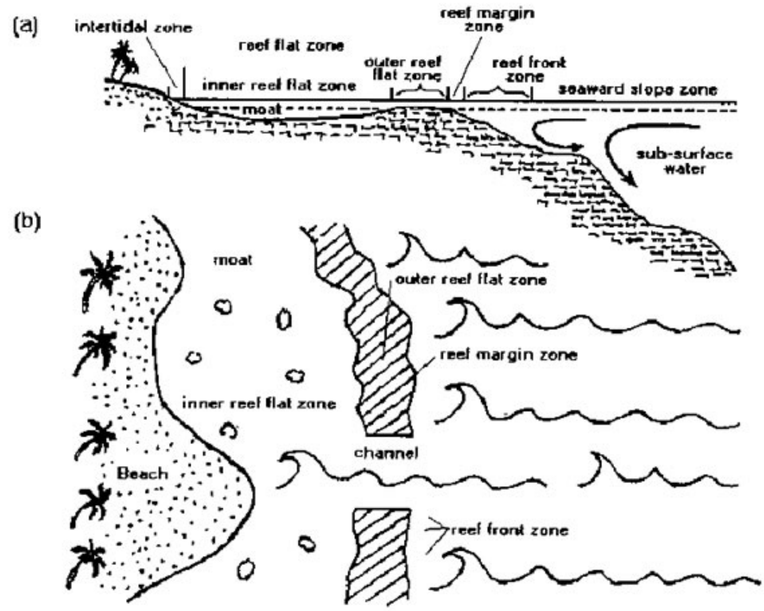


Figure 3.7. **(a) Reef structure near the coast (Modified from Myers 1991). (b) Conceptual model of coastal features that influence storm surge and coastal inundation. The reef front zone reflects and diverts much of the approaching water. Thus, only the water from storm surge and wind-driven waves that clears the top of the reef can cause inundation. Cuts (channel) in the reef can provide a channel for incoming water and produce large waves. (Modified from Guard 1995)**

3.4.3. Meteorological events that cause high wave events on Guam

Lander and Guard (1997) identified five primary meteorological events that produce non-seismic high wave events on Guam. Conceptual models of these meteorological events are shown in Figures 3.8, 3.9, 3.11, 3.12, and 3.13. The five meteorological events are:

a. Intense typhoon passing over the Island;

b. Large, slow-moving "solitary" typhoon passing southwest of the Island;

c. Strong westerly monsoon surge;

d. Strong typhoon accompanied by a monsoon surge; and,

e. Rapidly moving typhoon passing to the south.

3.4.3.1. Intense typhoon passing over the Island

Despite the fetch and duration limitations imposed by the relatively small size of the core of a typhoon, direct eye passage of an intense typhoon (i.e., greater than or equal to Typhoon Category 3 on the Saffir-Simpson Tropical Cyclone Scale (Section 5.3 and Appendix C) over Guam is usually accompanied by phenomenal waves on all shores exposed to the high winds in the eye wall. A schematic of the direct eye-passage scenario is shown in Figure 3.8.

When the eye of the typhoon passes close to a location, the winds in the core of the cyclone change direction rapidly as the cyclone translates past the location. This rapid change in wind direction limits the length and duration of the fetch, greatly diminishing the generation of large swells. In the high intensity core, the wind-driven waves dominate until the cyclone moves far enough away to allow the wind direction to become more constant and the duration of the fetch to increase. A change in wind direction of more than 30° to 45° necessitates that the fetch duration computation for fully developed seas begin again at zero hours. Thus, swell is normally not the primary concern on the lee side (usually west side) of the Island during the eye passage. Here, intensity is important to generate wind-driven waves. The island of Guam has little effect on changing the intensity of typhoons due to its small size and relatively low terrain.

The low pressure in the center of typhoons produces a hydrostatic increase in sea level (inverse barometer effect) near the center. For very intense typhoons, the sea level can rise 3-5 feet. This contributes to the total height of the wind-driven waves affecting a coastal location. The raised sea level is pushed forward in the direction of the strong winds, and constitutes a portion of the so-called "storm surge."

Table 3.5 shows the major typhoons from 1946 to 1997 passing across Guam with their significant meteorological and wave data. The wave data is generated from a parametric wave model or is taken from observations when available.

3.4.3.2. Intense, slow-moving "solitary" typhoons moving southwest of the Island

A large "solitary" typhoon passing southwest or west of the Island (Figure 3.9) can produce damaging waves on the southern and western coasts. By "solitary" it is meant that the typhoon is embedded in deep easterly flow without the interaction of monsoonal westerly winds. Very intense solitary typhoons passing close to the southwest side of Guam often produce phenomenal east-side waves, but do not generate much in the way of west-side waves. A good example of this is the passage of Super Typhoon Yuri (Nov 1991). Yuri produce phenomenal waves on the east side of the Island, causing near-historical inundation from Pago Bay at the north end to the Saluglula Pools and the Tipoco Cemetary in Inarajan at the south end. Figure 3-14 illustrates the wave heights observed during Super Typhoon Yuri, Typhoon Omar (Aug 1992), Typhoon Gay (Nov 1992), and Typhoon Paka (Dec 1997).

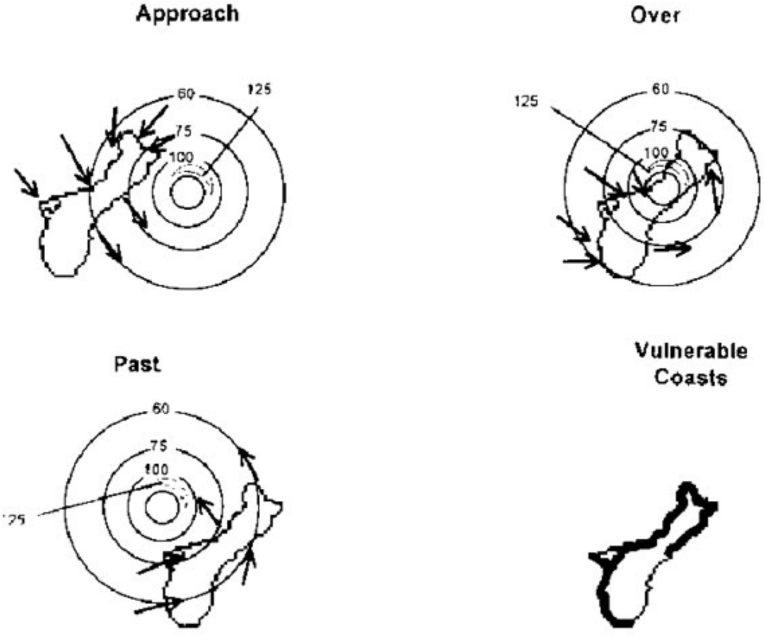


Figure 3.8. Depiction of destructive waves generated by an intense typhoon as it approaches, moves over, and passes to the west of Guam. Vulnerable coastlines are shown in the lower right.

Table 3.5. Major typhoons from 1946 to 1997 passing across Guam with their significant meteorological and wave data. MSWH is the model significant wave height and MSWP is the model significant wave period.

Month/ Year	Name	[illegible] (knots/mph)	Min Sea Level Pressure (mb)	[illegible]	Model Significant Wave Height	Model Significant Wave Period
05/76	Pamela	120/138	930	unk	22.6	12.9
12/97	Paka	125/144	940 est.	30 NW	22.2	12.7
11/62	Karen	135/155	910	14 W	19.9	12.1
08/92	Omar	110/127	940	12 N	17.5	11.4
11/84	Bill	85/98	970	unk	17.4	11.3
11/92	Gay	85/98	955	9 N	14.5	10.3
09/64	Sally	65/75	976	unk	8.0	7.8
11/77	Kim	6575	974	6 E	12.5	9.6
10/92	Brian	65/75	989	6 E	10.5	8.8
08/51	Marge	65/75	975	unk	13.7	10.1
10/82	Mac	60/69	980	unk	12.6	9.6
11/68	Ora	60/69	980	unk	6.2	6.9
08/79	Judy	50/58	990	unk	3.0	4.9
09/58	Ida	40/46	994	unk	1.5	3.4

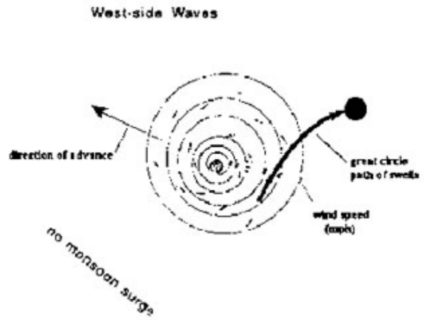


Figure 3.9. Large slow-moving "solitary" typhoon passing southwest of the Island. Heavy dot represents the west side of Guam. (Modified from Lander and Guard 1997)

There are three primary factors that act to inhibit the size of west-side waves produced by solitary intense typhoons passing to the south of Guam: (1) limited fetch distance on the south side of the tropical cyclone, (2) limited fetch duration on the south side of the tropical cyclone, and (3) the reduction of the radial extent of high winds on the south side of the tropical cyclone due to the effects of the speed of translation. The inhibiting effects of these limitations on the generation of high west-side waves may be counteracted by increased size of the tropical cyclone, a slower speed of translation, and closer proximity to the Island. Some large, slow-moving, very intense solitary tropical cyclones in recent history have produced large west-side waves; however, the largest west-side wave events have been associated with strong typhoons accompanied by monsoon surges, and by strong stand-alone monsoon surges.

The larger typhoons produce larger swells due to the larger fetch length and width. These swells decay more slowly outside the 35-kt (39-mph) wind radius because of the large swell width. The typhoon's large size also means that it will take longer for the 35-kt wind radius to clear the location, and thus, for the swell decay to begin. Figure 3.5 illustrates the relative differences between fetch length, fetch width, and decay distance for large and small typhoons passing the same distance from Guam. Because there is limited historical data of storm surge and inundation on Guam, two techniques were used to determine the swells that reached the Island. For large typhoons, the 35-kt (39-mph) wind radius often covered the Island, and a typhoon swell-generation model could be used without decay. For typhoons where the 35-kt (39-mph) wind radius was beyond the Island, a swell decay model was applied to the typhoon-generated swell.

3.4.3.3. Strong westerly monsoon surges

Guam is not in a true monsoon regime. Occasionally, the low-level wind flow in the tropics of the western North Pacific may become organized into a defined monsoon trough, which accompanies an extensive band of southwesterly low-level wind flow stretching from the Philippines, eastward to sometimes as far as the international date line. The regions that this monsoon "surges" across is referred to as an *episodal monsoon regime*. Guam is in such a regime. The strongest southwesterly winds are usually present in a relatively narrow (100 to 200 n mi) ribbon within the broader region of southwesterly wind flow south of the trough axis. The southwesterly winds may be shallow (up to 5,000 feet) and weak (< 15 mph sustained winds at the surface), producing a few (1-3) episodes of heavy rain per day over a location, often in the form of thunderstorms. This is the *weak (monsoon) surge*. A *moderate (monsoon) surge* occurs when the southwesterly winds deepen (up to 20,000 feet) and intensify (15 to 30 mph at the surface). Weather associated with the *moderate (monsoon) surge* is several (3-6) episodes per day of heavy rain, extensive periods of light rain, and heavy overcast skies with embedded thunderstorms. At times, the monsoon southwesterlies can get very deep (over 30,000 feet) and intensify to "gale force" (35-60 mph) over a long fetch of 500 to 1000 n mi. This is a *strong (monsoon) surge*. An additional feature of a *strong monsoon surge* is the presence of eastward-moving monsoon squall lines in the zone of highest winds and most extensive monsoon cloudiness. Its weather is characterized by frequent (6-12) episodes per day of very heavy rain in squalls and nearly continuous light rain. There is usually little or no lightning associated with strong surges. The vertical structures of the various monsoon surges are diagramed in Figure 3.10. The characteristics of the weak, moderate, and strong surges are summarized in Table 2.3, and the monsoon climatology for Guam is shown in Table 2.4.

These strong monsoon surges can last from a few days to more than two weeks. They can cause large wave events on the western part of Guam. One of Guam's largest west-side wave events occurred with a very strong monsoon surge, which occurred in August 1974. On Guam, the narrow ribbon of gale force winds blew across the Island for nearly a week with maximum wind gusts recorded at near 55 kt. Phenomenal west-side waves occurred, and caused considerable coastal erosion. The 700-ft, 40,000-ton passenger liner CARIBIA was being towed to Taiwan for salvage, when ocean tugs had to cut loose their tow. The CARIBIA sank at the mouth of Apra Harbor. At the time of this surge, Typhoon Mary was developing 485 n mi to the northwest of Guam, at the head of the surge and to the north of a monsoon gyre (Lander 1994, 1996). Figure 3.11 illustrates the horizontal structure of the southwest monsoon surge, the anchoring monsoon gyre to the west of the surge, and the developing tropical cyclone northwest of the surge. The surge does not necessarily need to be associated with a developing tropical cyclone, but they are commonly found in tandem.

Strong onshore southwesterly winds may change the character of the breaking waves to a higher proportion of spilling versus plunging waves. Another consequence of strong

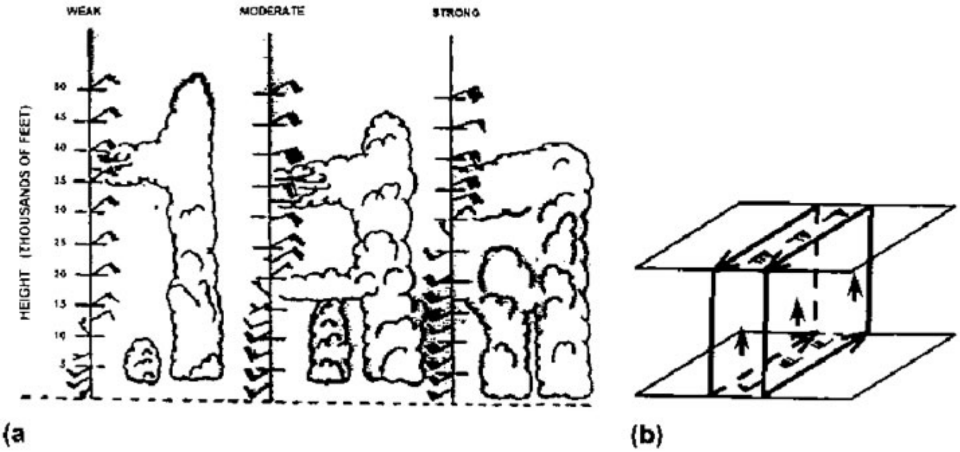


Figure 3.10. Schematic diagram of (a) vertical wind and cloud structure of various strengths of monsoon surges (weak, moderate, and strong), and (b) general low-level flow, upper-level flow, and induced vertical motion associated with the monsoon. Wind barbs are in knots (half barbs are 5 kt, full barbs are 10 kt, and flags are 50 kt). (From Guard 1986)

onshore southwesterly winds is a greater inland transport of sea spray with a commensurately greater inland defoliation or killing of vegetation, since the wind direction is aligned with the wave direction.

3.4.3.4. Strong typhoon accompanied by a monsoon

Some of the largest west-side waves recorded on Guam have been the result of the close passage of a "strong" typhoon to the south of the Island and the added structural feature of a significant monsoon surge accompanying the typhoon on its southwestern flank. The characterization of the typhoon as "strong" is meant to imply a larger-than-average radial extent of typhoon-force (65-kt/75 mph) and storm-force (50-kt/58-mph) wind. A superposition of a monsoon surge and a typhoon southwest of the Island, as shown in Figure 3.12, can cause large waves on the west side of Guam. Two of the largest west-side events occurred with this monsoon-tropical cyclone pattern—Andy (1982) and Dale (1996). The high waves produced are hypothesized to result from the enhancement of high seas already produced by the long fetch of the monsoon gales as they pass through the typhoon- and storm-force regions of a strong typhoon. Emerging from the eastern side of the typhoon, the reinforced large waves then travel a small decay distance to the western shores of Guam.

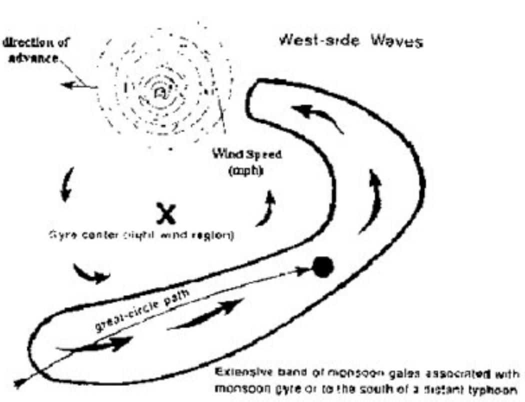
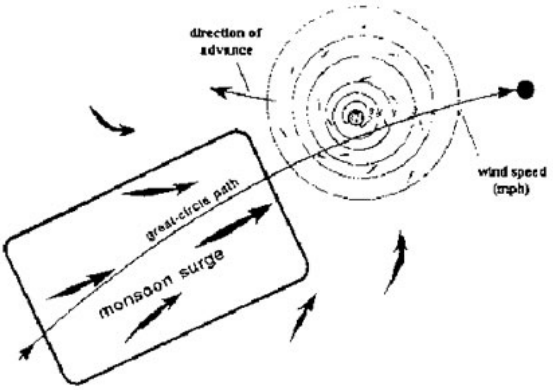


Figure 3.11. Conceptual model of the horizontal structure of a strong monsoon surge. The model also shows the anchoring monsoon gyre to the west and the developing tropical cyclone to the northwest. Bold arrows indicate low-level wind flow. The long arrow indicates the great circle path of waves/swells to Guam. Heavy dot represents the west side of Guam.

3.4.3.5. Rapidly-moving typhoon passing south of the Island

Phenomenal waves are more common on the east side of Guam. The favored motion of tropical cyclones in the area contribute to this. Sixty percent of all tropical cyclones that have passed within 180 n mi of Guam have approached the island from the east through the southeast. An additional 19 percent have approached the Island from the southeast through the south and seven percent from the northeast through east. Thus, 84 percent of tropical cyclones which have passed within 180 n mi of Guam have had a westward component to their motion. Typhoon Olive (April 1963) was the only tropical cyclone during the period 1946 to 1997 to severely affect the Island while moving toward the north-northeast as it passed. A large, fast moving typhoon approaching from a southeast direction, as shown in Figure 3.13, produces damaging waves on the east and southeast sides of the Island.

Westward moving tropical cyclones produce the highest wind and sea conditions (northeast side) on Guam if they pass over or to the south of the Island. This arises due to the fact that the speed of translation combines with the tropical cyclone wind to produce the highest winds and the greatest radial extent of high winds on the right side. In addition to these higher winds, there is another factor that accounts for extremes of sea and swell on the north side of a westward moving typhoon: the patch of highest wind speed translates across the sea surface in the same direction as the seas which are being



Worst Case West-side Waves

Figure 3.12. Conceptual model of a strong monsoon surge accompanied by a strong typhoon. The bold dot represents Guam. Short arrows indicate low-level winds associated with the monsoon. The long arrow is the great circle route of the waves to Guam. Heavy dot represents the west coast of Guam.

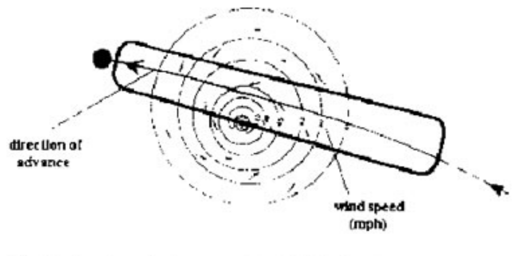
generated. This allows the seas to develop to a higher state than otherwise because of the "virtual" fetch and duration created by the artifact of the wind patch moving with the wave train which it is generating. The speed of deep water ocean waves is dependent on the height and the period of the waves. The slower short-period waves move on the order of 25-30 mph and the long-period waves move at speeds of up to 45 mph. Thus, at the normal 14 mph translation speed of tropical cyclones in the deep tropics, the waves generated by the tropical cyclone outrun it in all directions. If the tropical cyclone is moving at an unusually rapid speed of translation, then it is possible that it may nearly keep up with the waves that it is generating in the direction of its travel. This, in turn, allows the waves located in the right side of a rapidly moving tropical cyclone to build to a much higher state than they otherwise would if the tropical cyclone were moving more slowly. Translation speeds of 17 mph or more, are however, sufficient to allow the tropical cyclones to generate much higher seas and swell than slower moving tropical cyclones. On the south side of a tropical cyclone moving rapidly to the west, the "virtual" fetch and duration are shortened by the translations of the tropical cyclone. The sea and swell generated on this side of the tropical cyclone is therefore much lower than the sea and swell generated on the north side. This is why intense, rapidly moving tropical cyclones that pass north of Guam normally don't produce damaging swells on the west side of Guam.

3.4.4. Inundation heights on Guam from recent historical typhoons

Figure 3-14 shows inundation heights from recent typhoons affecting Guam. In the figure, Typhoon Yuri (a) passed 80 miles south of Guam, Typhoon Omar (b) and

Worst Case East-side Waves

Translation Speed in Excess of 15 kt creates "virtual" Fetch in Dangerous Semicircle of TC



(No significant west-side waves unless CAT 3, 4, or 5 TC passes directly over island)

Figure 3.13. Rapidly-moving typhoon passing south of the Island. The solid dot represents the east side of Guam and the rectangular box is the path of maximum wave/swell propagation. Arrow indicates the great circle path of the swells.

Typhoon Gay (d) passed over the center of the Island, and Typhoon Paka (c) pass just north of the Island. Yuri, a large, intense, fast-moving typhoon moving south of the Island produced the largest east side waves.

3.5. TORRENTIAL RAINS AND FLOODING

Rainfall associated with tropical cyclones, especially intense typhoons, is highly variable and extremely difficult to measure. Rainfall is generally higher in mountainous areas than over flat terrain. The mountains act as a barrier to the flow and lift the warm moist air, enhancing condensation and rainfall. This process is most efficient when mountains extend above the 5,000-8,000 foot level, significantly higher than the mountains on Guam. At La Reunion Island, a mountainous island in the South Indian Ocean, Cyclone Denise dropped 45 inches of rain in 12 hours and 71.8 inches in 24 hours. Over 40 inches were recorded during a typhoon passage in Baguio, Philippines. However, there have been cases when very large rainfalls occurred over areas of relatively low relief. Typhoon Emma (1959), dropped 42.4 inches of rain during a 24-hour period on Okinawa, but this may have been in conjunction with a mid-latitude weather system. Because the highest terrain on Guam is slightly over 1,300 feet and because the Island is not affected by mid-latitude weather systems, it is not likely that Guam will experience these extreme rainfall events. It is valid to assume that rainfall is somewhat heavier over the mountains of Guam than over the lower areas where the rain gauges are located.

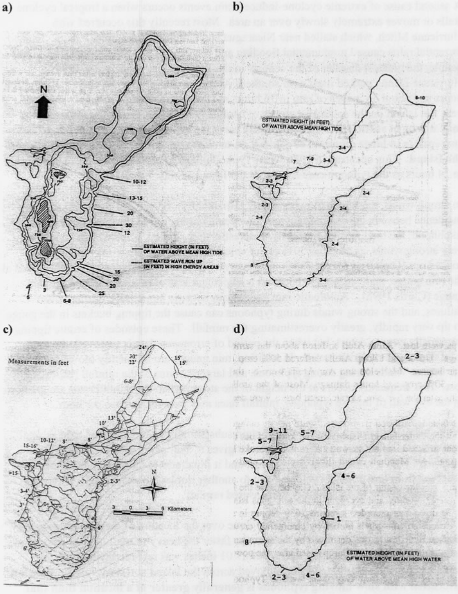


Figure 3.14. Observed maximum wave heights (in feet) during (a) Typhoon Yuri, (b) Typhoon Omar, (c) Typhoon Paka, and (d) Typhoon Gay. (From JTWC 1991, 1992; Guard 1998)

A second cause of extreme cyclone-induced rain events occurs when a tropical cyclone stalls or moves extremely slowly over an area. Most recently this occurred with Hurricane Mitch, which stalled near Nicaragua and Honduras for almost 2 days. The torrential rains caused monumental flooding and mud slides that killed more than 9,000 people, the greatest disaster of the century in the Western Hemisphere. In 1997, Hurricane Danny parked itself over southern Alabama, dumping 25.98 inches of rain in 7 hours and about 36 inches of rain in 36 hours at Dauphine Island, Alabama. This is a very flat island on the southwest corner of Mobile Bay. **Thus, while Guam's terrain may not be of sufficient height to greatly increase rainfall amounts, the Island is susceptible to large amounts of rainfall do to slow tropical cyclone movement across the Island.** This occurred in 1976 when Typhoon Pamela dropped over 27 inches of rain in 24 hours as the typhoon crawled across the Island at only 7 mph.

In strong winds, the rain is blowing nearly horizontally. Because of the sharp angle of incidence between the driving rain and the opening at the top of the rain gauge in all likelihood, the total rainfall is grossly underestimated. In fact, it is surmised that during very strong winds, as much as 50% of the volume of rain in a gauge may be blown or sucked out (Dunn and Miller 1964). For every 10 kt (11.4 mph) increase in wind speed at the rain gauge, there appears to be about a 10 percent loss of rainfall entering the rain gauge (Curtis 1995). Automatic rain gauges can become inoperative during power failures, and the strong winds during typhoons can cause the tipping buckets in the gauge to tip very rapidly, greatly overestimating the rainfall. These episodes of erratic tipping are usually easy to detect, but when the period of erroneous data is removed, the total rainfall is again underestimated. In addition, rain gauges are frequently blown away by the intense winds during strong typhoons, and large portions of the rainfall record are lost. This frequently occurs at the height of the storm, when the rainfall rates are greatest. In the eye wall of intense typhoons, rainfall rates may exceed 5 inches per hour.

While historical rainfall records may contain substantially underestimated total rainfall amounts, the information is still valuable. It gives a "ball park" idea of the rainfall associated with a specific tropical cyclone, and it illustrates the high variability often observed from one tropical cyclone event to another tropical cyclone event. There are several reasons for this variability in measured rainfall:

(1) The speed of motion of the cyclone over the location of the rain gauge is very important. The faster the cyclone moves, the faster the heavy rainfall regions pass across the gauge. The largest 24-hour rainfall of 27.01 inches was recorded with Typhoon Pamela in May 1976 while the storm moved across the Island at a slow 7 mph. **Rainfall associated with slow moving typhoons is generally greater at a location than that associated with fast moving typhoons of comparable intensity and proximity.**

(2) The location of the eye wall, major rain bands, or dry slots between major rain bands is very important. During Typhoon Dale (Dec 1996), central Guam spent several hours in a dry slot between rain bands, where strong winds blew salt water

through the air, but little rain fell. A few miles to the north and a few miles to the south, major rain bands dropped rain at a rate exceeding 1 inch per hour.

(3) The characteristics of the eye wall and rain bands can cause significant differences in rainfall among tropical cyclones. Intensifying typhoons will likely produce heavier rain than weakening typhoons. On rare occasions, atmospheric conditions can lead to drastic weakening, even over water. In November 1992, Typhoon Gay became a very "dry" typhoon. When Gay approached and crossed the Island, the north part of the eye wall had been sheared off, leaving the cloud tops below 15,000 feet. As a result, only 3.59 inches of rain fell in the northern part of the typhoon, despite the eye passing over the center of the Island. As a result of the low rainfall, large amounts of salt were deposited across the northern half of the Island.

Table 3.6 shows the largest historical tropical cyclone-related rainfall events on Guam. The largest 24-hour rainfall of 27.01 inches was recorded with Typhoon Pamela in May 1976. It is interesting to note that the occurrence of Pamela added nearly 1 inch of rain to the official monthly average rainfall for May, which is based on a 30-year rainfall record. Nearly half the heavy rain events on Guam occurred from cyclones that were less than typhoon intensity. In typhoons, the heaviest rains are concentrated near the eye and thus the typhoon must pass relatively close to the Island. Heavy rains in weaker systems are more unorganized and may extend much farther from the center. They can therefore drop heavy rains while passing some distance from the Island. For example, a tropical cyclone developing about 200 n mi north-northeast of Guam dropped 3.75 inches of rain on 11 and 12 September 1998, as a monsoonal tail stretched across the Island (13 Sept 1998 PDN).

Flooding **occurs whenever rainfall accumulates in an area faster than it can drain off or can be absorbed by the soil.** Flooding, while not a widespread problem at this time on Guam, will continue to increase as more and more of the natural drainage of Guam is restricted and diverted. Construction of highways, housing subdivisions, and commercial properties will continue to restrict and divert the Island's natural drainage. As land becomes scarcer, there will be additional pressure to build in flood-prone areas. **Guam must update flood plain maps and take the necessary actions to restrict building in such areas. Once the action is taken, it must be enforced.**

During the height of typhoons, rain rates can exceed 5 inches per hour, even over flat terrain. Dunn and Miller (1964) noted a 6-inch accumulation in 75 minutes in Hialeah, Florida during the passage of a hurricane. But mountainous areas such as La Reunion in the South Indian Ocean and Baguio, Philippines have produced considerably higher rain rates. On Guam, in recent history, the highest recorded hourly rain rate was in TS Virginia where 3.43 inches fell. However, it is likely that rain rates were higher with the eye passage of intense typhoons such as Typhoon Pamela (May 1976), Typhoon Karen (Nov 1962), Typhoon Omar (Aug 1992), and Typhoon Paka (Dec 1997), even though rain gauge destruction or malfunction and power outages prevented accurate

Table 3.6. Maximum 24-hour rainfall totals on Guam (1918-1997).

TROPICAL CYCLONE	DATE	AMOUNT (IN)	LOCATION	CPA (n mi)
TY PAMALA	May 76	27.01	Taguac	0
(UNNAMED TC)	Oct 24	24.5	Agana Agri. Stn	Unk
TY PAKA	Dec 97	20.00 est.	Andersen AFB	N 20
TS ALICE	Oct 53	18.33	Taguac	N 15
TY OMAR	Aug 92	15.36 est.	Taguac	0
TS CARMEN	Oct 86	11.98	Taguac	WNW 14
TROPICAL DISTURBANCE	Feb 80	10.89	Nimitz Hill	Unknown
(UNNAMED TYPHOON)	Jul 18	10.5	Unknown	Unknown
TS TIP	Oct 79	10.14	Taguac	S 40
TY AMY	May 71	9.92	Taguac	SSW 90
TS IDA	Oct 69	9.38	Taguac	NNE 90
TY HUNT	Nov 92	8.19	Andersen AFB	NNE 20
TS IRMA	Feb 53	7.88	Andersen AFB	S 90
TS PEGGY	Jul 86	7.86	Taguac	W 12
TD (POLLY)	Aug 71	7.81	Taguac	NNE 85
TS VIRGINIA	Sep 65	7.48	Taguac	NE 130
TS MARY*	Aug 74	7.36	Taguac	NNE 485
TY YURI	Nov 91	7.10	Andersen AFB	SSW 70
TY NINA	Aug 53	7.07	Andersen AFB	N 15
TY ROY	Jan 88	6.45	Taguac	WNW 12
TD (BABE)	Apr 74	6.37	Taguac	E 40
TY BRIAN	Oct 92	6.37	Taguac	0
TS ORCHID	Sep 80	6.34	Taguac	N 75
TY KAREN**	Nov 62	6.32	Taguac	0
TY RUSS	Dec 90	6.12	Nimitz Hill	SSW 50
TY SUSAN	Dec 63	6.09	Taguac	N 75

* Mary was 485 n mi NNE; rain came from deep monsoon surge feeding into Mary.

** Power to rain gauge failed during Karen. Observation was taken day after Karen's passage. Significantly higher amounts likely occurred during passage. Karen's CPA was changed from S 10 to 0 based on reanalysis of data. (Table modified from Tropical Cyclones Affecting Guam (JTWC 1991)).

measurement of the event. This brings up the fact that **Guam needs more reliable and more survivable rain gauges.** Table 3.7 shows some of the maximum hourly rainfall amounts recorded at Taguac, Guam from 1957 to 1997.

Historically, flood damage associated with tropical cyclones has not been well documented. When a Presidential Disaster Declaration is made, it usually involves substantial wind damage or inundation. Residences in the areas most vulnerable to flooding are largely wooden, and are frequently damaged to the extent that flood damage is attributed to the wind. As a result, flood damage is generally combined into the total damage computations. For the most part, flooding that occurs to concrete structures is relatively minor, and often does not exceed insurance deductible amounts. Thus, it is not reported or claimed. An exception to this is where concrete structures are near streams and rivers where water spills over the banks or storm surge causes the water to back up in near coastal areas. The eastern coastal areas of Pago Bay and the lower Pago River are susceptible to such flooding.

Table 3.7. Maximum tropical cyclone-induced hourly rainfall amounts of greater than 1.5 inches per hour occurring on Guam from 1957-1996. (Modified from JTWC 1991)

[illegible]	[illegible]	[illegible]
TYs Pamela/Karen,/Omar/ Paka	21 May 76/11 Nov 62/ 28 Aug 92/16 Dec 97	These storms may well have had rain rates >3.5"/hr
TS Virginia	13 Sep 65	3.43
TD (Ivy)	19 Oct 77	3.21
TD (Joan)	25 Aug 59	2.82
TS Emma	02 Oct 62	2.13
TY Amy	12 May 71	1.83
TY Wendy	11 Jul 63	1.79
TS Ida	16 Oct 69	1.73
TS Tip	10 Oct 79	1.61
TS Orchid	09 Sep 80	1.54

Street flooding is common in Guam, and many storm drains can't handle more than 1-inch-per-hour rain. In fact, rains of this intensity will cause many of the man hole covers of storm drains, especially on Marine Drive and in Tumon, to pop up as a result of the water pressure. These areas are more susceptible to slower drainage because the elevation difference between the roads and the sea level is small, and gravity is not much of a factor in helping the drainage of the storm drains. During the height of typhoons, rain rates can exceed 4-5 inches per hour, far exceeding the capacity of the drains. Since the storm drains discharge into the ocean, the water may back up if the sea level rise due to storm surge brings the level of the ocean up to the level of the drain pipes. Another problem that prolongs the street flooding is that the storm drains get covered with large volumes of debris. This causes water to fill up the streets instead of flowing into the storm drains. **As the number of streets increase on Guam, the problem of street flooding will increase proportionally. The capacity of storm drains to handle the increased runoff, especially on roads that are near sea level, must be addressed. The solution may not simply be to increase the capacity of the drains.**

Flooding that occurs in near coastal areas is almost always attributed to the *inundation* associated with *storm surge* and *wind-driven waves*. In locations where there is a rise in ocean levels from the *storm surge* and *wind-driven waves*, the raised level of the sea prevents the rivers and streams from draining into the ocean. As a result, the water backs up, and further flooding results. It is logical to assume that if the sea level had not been raised, the river water would have drained normally and flooding would not have occurred or would have been less severe. As a result, flood damage is generally combined into the total damage computations. (See Section 3.4 of this Chapter—Storm Surge, Wind-Driven Waves, and Inundation.)

The heavy rainfall rates greater than 1 inch per hour that can occur with tropical cyclones can lead to *flash floods*. These types of floods are most likely in the valleys of the more mountainous areas of Guam, and at this time, they do not appear to have caused significant damage to populated areas in the past.

3.6. WIND SHEAR AND MECHANICAL TURBULENCE

The air above the Island, especially in the lower 3,000 feet, is subject to considerable *wind shear* and *mechanical turbulence*. *Wind shear* refers to the change in wind speed and/or wind direction with height. Friction at the Earth's surface causes the wind to slow down as it gets closer to the surface and to turn more sharply toward the center of the cyclone as it gets closer to the surface. The friction over land is generally stronger than over water, and thus, the slowing and turning of the wind is greater over land than over water. Friction also increases with the roughness of the terrain, so the more mountainous terrain to the south will accentuate the slowing and turning of the wind more than the flatter terrain to the north. The percentage of slowing and turning also increases as the wind speed increases. Thus, in strong wind events such as tropical cyclones, the change in wind speed and/or wind direction with height will be significantly larger than under normal wind conditions. The *wind shear* process is illustrated in Figure 3.15(a).

Mechanical turbulence occurs when the prevailing wind hits a barrier, such as a mountain, a cliff, or a bluff. Part of the air moves laterally around the barrier, but a large portion of the air rises abruptly. Once the air clears the barrier, it begins a compensating sinking motion. This rise and fall is carried down stream in the form of a sinusoidal wave. The process is accentuated by higher mountains, stronger winds, and an unstable environment, which exists in the vicinity of a tropical cyclone. The *mechanical turbulence* process is illustrated in Figure 3.15(b). Another source of *mechanical turbulence* can also occur as a result of thermals that form from differential heating of the surface. Since during typhoons, there is usually heavy cloud cover, the differential heating is minimized, and is not generally a significant source of *mechanical turbulence*.

***Wind shear* and *mechanical turbulence* are primarily hazards to aviation.** After a cyclone moves away from Guam, there is a tendency to want to open the airfield as soon as surface winds fall below 50 kt (57 mph) and the crosswind component of the wind falls below 30 kt (34 mph). However, winds at 1,000-3,000 feet above the surface can be much stronger and different in direction than those at the surface. If this change in speed and/or direction exceeds a certain threshold, it can effect the lift of the aircraft, which could result in hard landings, or short and long takeoffs and landings. **Airport officials should check with the National Weather Service to determine the *wind shear* and *mechanical turbulence* hazards before reopening the airfield.** A weather balloon sounding should be made to determine the wind shear if the necessary information cannot be obtained from the NEXRAD. It will be difficult to get a timely balloon sounding in high winds until the National Weather Service has a new building with an adequate inflation tower.

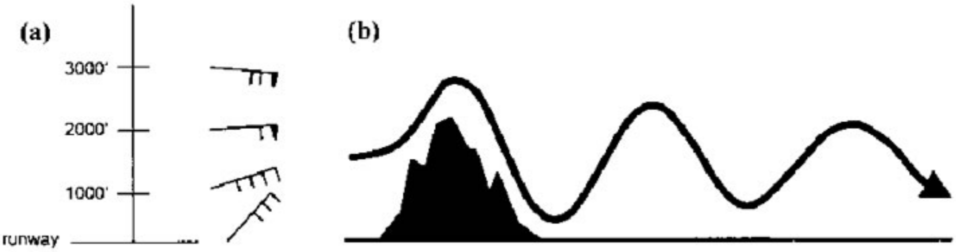


Figure 3.15. Models depicting the process of (a) vertical wind shear at the periphery of the typhoon, and (b) mechanical turbulence over Guam.

3.7. ROUGH SEAS AND SURF (Also See Section 3.4 -- Storm Surge and Inundation)

Tropical cyclones produce high seas that are proportional to the strength of the wind and the *fetch* of the wind. The *fetch* of the wind is the area over which the strong wind field blows. It has both length and width (see Figure 3.5). The seas/swells become fully developed after the wind blows over a sufficient fetch length >500 miles) for about 24-36 hours. Tropical cyclones create swells that emanate from the region just outside the cyclone's center or eye. These swells are reinforced by the stress of the wind across the sea. The swells travel at a preferred velocity of around 23 kt (26 mph), usually faster than the motion of the cyclone. As a result, the swells arrive at a location well ahead of the arrival of the cyclone itself (sometimes two to three days ahead). The size of the swells decrease (decay) as they move away from the strong reinforcing wind field (usually outside the 35 kt/40 mph wind band), so the swells get larger as the cyclone gets closer.

A large, slow moving cyclone several hundred miles away that never comes near the island produces large swells that move away from the center just like the circular ripples that develop when a rock is dropped into a pool. These large swells can travel hundreds of miles, and can be a hazard to ships at sea, especially for small recreational boats. When those swells arrive at the reef margin, they cause the surf to build dramatically. The weather may be perfect, and people are often caught by surprise by the waves and surf, which can be especially dangerous at high tide. Several of the drownings on Guam have been as a result of swells produced by unassuming storms up to a thousand miles away. Most commonly, this occurs with large, intense slow-moving tropical cyclones that take a track south of Japan. They generate large swells that suddenly arrive at the reefs on the west side of the Island from Ritidian Point to Asan Bay, producing rugged surf and strong rip tides.

During late July, August and September, strong southwest monsoon winds that may be indirectly associated with a developing tropical storm hundreds of miles to the north may surge across Guam for as long as two or three weeks. The southwest winds may be 40-60 mph in a narrow band from near the Philippines to Wake Island. Strong winds that blow more than 30-36 hours over a long *fetch* can generate very high (fully-developed) seas. seas from 18 to 30 feet high. These waves are dangerous to even large ships at sea. When the high, persistent waves hit an island such as Guam, they can cause considerable coastal erosion on the west side of the Island, and can prevent ships from entering or leaving the narrow mouth of the harbor for an extended period of time. (See Chapter 2, Section 2.5.2. and Chapter 3, Section 3.4.3.3.)

Figure 3.16 shows the kind of waves that were generated by Typhoon Dale (Nov 1996) as it passed southwest of Guam (see Section 3.3.3.4.). The gigantic waves are seen striking Orote Point on the west side of Guam. The tops of the waves running up the face of the cliff are nearly 100 feet high. The waves caused very serious erosion from Ritidian Point to Asan Bay. Figure 3.17 shows the scouring caused by "green" water thrown more than 80 feet into the air at the U. S. Navy housing area at South Tipalao at Naval Activities

3.8. TORNADOES

In the continental United States, in India, and in China, tornadoes frequently accompany landfalling tropical cyclones, especially typhoons. In island environments, tornadoes are not so frequent; in fact, documented cases are rare. On Guam, there has not been a verified occurrence of a tornado accompanying a tropical cyclone. There has been speculation in the past, but most of the speculation has been in the form of unsubstantiated responses to explain unanticipated damage. While tornadoes may have (could) accompany very intense typhoons, it is likely that their winds were not (will not be) significantly stronger than the typhoon itself and that the tornado damage was (will be) masked by the general destruction of the typhoon. **Compared with the typhoon wind hazard risk, the tornado risk is very small on Guam.**

3.9. SEA SALT DEPOSITION

When tropical cyclones lash the Island, the air and rain water contain large concentrations of salt. The stronger the winds are, the greater the concentration of sea water that is carried to the Island and the greater distance inland it is carried. The concentration of salt in the air became very graphic during Typhoon Gay in November 1992. When Gay approached and crossed the Island, the north part of the eye wall had been sheared off, leaving the cloud tops below 15,000 feet. As a result, little rain fell in the northern part of the typhoon, and large amounts of salt were deposited across the northern part of the Island. In coastal areas, sand that is normally washed away by the rain was embedded in trees and wooden buildings. Without the rain, it is likely that salt was deposited in every crack and crevasse in buildings, power substations, vehicles, etc. It was deposited on power lines, transformers, pumps, generators, vegetation, and most other exposed surfaces. Visibly, the salt deposition devastated the vegetation of northern Guam. Nearly 4 years was required for its full recovery. Less visible and immediate was the corrosion caused by the layer of salt. Even with rain, salt in lower concentrations is carried into cracks and crevasses where it eventually works its corrosive power. *The sea salt*

4.2.2. Western Pacific historical data base

The historical TC record available for the western North Pacific is reasonably adequate for the purposes of the HURISK Model. The record begins with the year 1945. Through the 1997 season, this consists of 1471 TCs, 930 or about 63% that reached to at least typhoon intensity at some point over the western North Pacific TC basin. The basin includes that portion of the western North Pacific west of the international date line onto the Asian continent as well as adjacent land areas. TC forecasts for US interests in that and many of the other global TC basins are provided by the Joint Typhoon Warning Center (JTWC), located at Pearl Harbor, Hawaii (JTWC was located at Nimitz Hill, Guam, from 1959 until January 1999).

The TC tracks and intensities used by the western North Pacific HURISK Model are those officially issued by the JTWC and documented in annual issues of the Annual Tropical Cyclone Report. The storm track file is routinely updated by SAIC at the conclusion of each typhoon season. Additionally, SAIC has made some modifications to the original JTWC storm track file. These changes, mostly to earlier storms, were prompted by the examination of TC tracks in connection with use of the HURISK Model over Asian portions of the basin. Guard (OFCM, 1995) pointed out many serious problems with TC intensity data bases in general. Additional improvements to the data bases are underway by Guard and Lander at the University of Guam and by Neumann at SAIC.

It was not until 1945 that formal TC reconnaissance began in the western North Pacific and the records were complete enough to allow computer processing of the data. Even with aircraft reconnaissance, the position and intensity of some remotely located TCs were difficult to establish.

In the mid-1960's, satellite surveillance provided more detailed information on location and intensity of even remotely located storms. Thus, greater uncertainties as to the TC intensity and location are to be expected in the pre-satellite years. Aircraft reconnaissance was discontinued over the western North Pacific in 1987 and satellites are now the main TC reconnaissance platforms in the basin. In 1994, the Next Generation Weather Radar (NEXRAD) was installed on Guam and has since provided invaluable track and intensity data on TCs affecting the southern Mariana Islands. However, the effective range of the NEXRAD is 250 n mi for reflectivity data (clouds and rain signatures) and 125 n mi for Doppler wind signatures. Thus, the TC must be relatively close to the islands before the radar can provide reconnaissance-quality data. Despite the earlier aircraft, the satellites, and the Doppler radar, it should be realized that precise measurement of surface wind conditions in TCs exists only from surviving ground-level instrumentation.

deposition comes from two processes. Ocean spray from the sea surface is carried into the tropical cyclone by the near surface winds. It is lifted and is mixed with the rain. While the concentration of salt in the rainwater is not known, the taste of salt is detectable. The second process comes from the impact of large waves against the cliffs and rocks of the Island. The force of the collision sends sheets of salt water into the air and the strong winds carry the sea spray inland. **It is likely that none of the Island escapes the deposition of salt during even a weak tropical storm, but areas near shore feel the greatest effect. Salt deposition is the single most detrimental hazard to Island agriculture.**

3.10. EROSION AND POLLUTION

The torrential rains, strong winds, and salt deposition can all play a role in increasing Island erosion. The torrential rains wash tremendous amount of soil and debris into rivers, which then deposit much of it onto the reefs surrounding Guam. This deposition of silt and debris is highly detrimental to the health of the coral polyps that create and maintain the reefs. The erosion and pollution hazard to coral was not addressed until the aftermath of Super Typhoon Paka. A recovery assistance program funded jointly by the Federal Emergency Management Agency (FEMA) and the National Oceanic and Atmospheric Administration (NOAA) contracted local divers to remove the debris from the reefs following Paka. The debris removal process from the southern reefs took divers several weeks and culminated in the removal of more than 21,000 pounds of debris. **This reef recovery program was very successful, and should be made available following typhoon- and flood-related Presidential Disaster Declarations for Guam.**

After most heavy rain events on Guam, the *ecoli* bacteria counts exceed acceptable levels in many of the bays around Guam. The source of this bacteria is largely from animal fecal material that is washed into the bays. An alternate source may be from sewers that overflow. This can especially be a problem when power failures make sewage booster pumps (lift stations) inoperative, or when booster pumps cannot handle the volume of sewage. When typhoons affect the island, the associated rough water can damage the sewage out falls, which channel sewer water (with solids removed) to the open ocean. This allows minimally treated sewage to drain much closer to shore than it is supposed to. This condition often lasts until the out fall is repaired, which may require months. Damage to out fall pipes occurred during Typhoon Pamela (May 1976), Typhoon Dale (Dec 1996), and Typhoon Paka (Dec 1997). Typhoon Dale was not especially intense on Guam, but it produced very damaging waves on the west side of the Island. It is not known how typhoon-induced changes in currents and surges affect the normal flow of the sewage out falls, but one would assume that the vertical mixing by the rougher ocean would allow some of the sewage to be deposited in the near-coastal waters and on the beaches. **Study is needed to determine the behavior of the sewage from level II treatment during tropical cyclones.**

On 10,11, and 12 September 1998, a developing tropical cyclone dropped about 4 inches of rain. Weekly analyses conducted by the Guam Environmental Protection Agency