A SCALE RELATING TROPICAL CYCLONE WIND SPEED TO POTENTIAL DAMAGE FOR THE TROPICAL PACIFIC OCEAN REGION: A USER'S MANUAL

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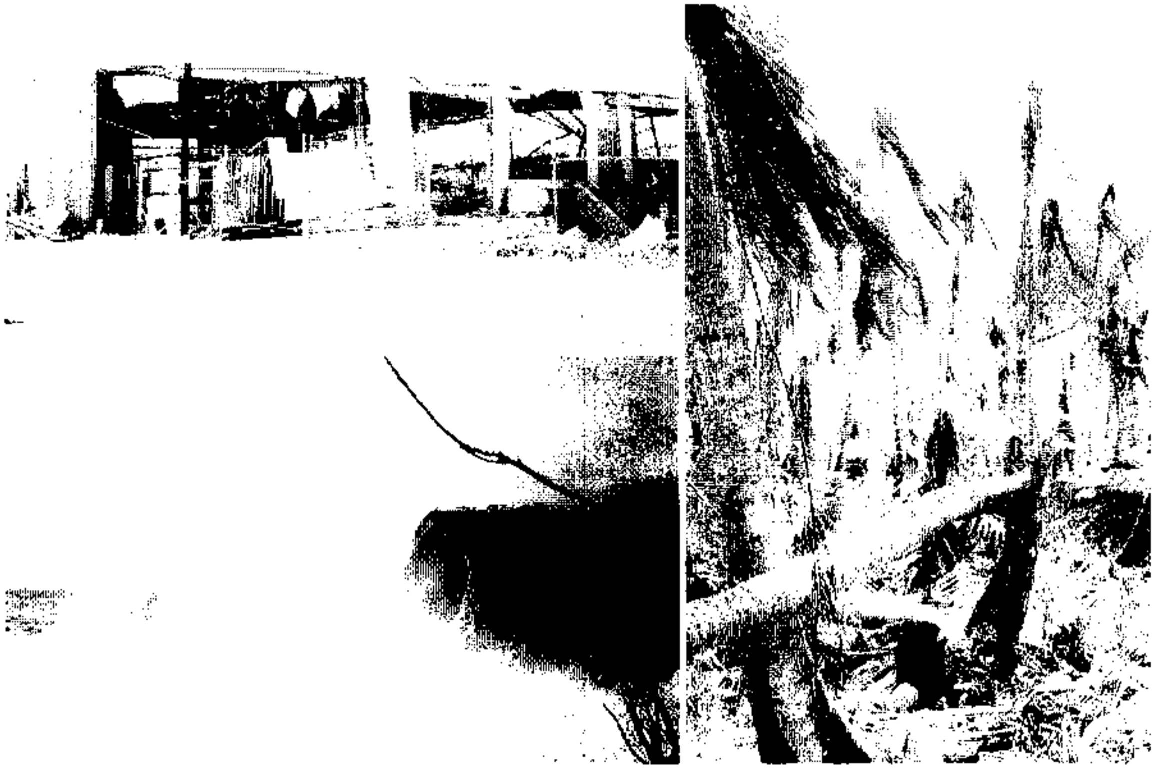

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A Scale Relating Tropical Cyclone Wind Speed to Potential Damage for the Tropical Pacific Ocean Region:
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I. INTRODUCTION

This *User's Manual* describes the development and application of a scale that relates tropical cyclone wind speed to the potential damage to structures and vegetation (primarily trees) for coastal areas of the tropical Pacific Ocean. It also relates the wind speed to coastal wave action associated with the attendant tropical cyclone. The primary use of the scale is to enable emergency managers and other interested decision-makers to better understand the risk associated with a particular tropical cyclone wind speed. This should allow the decision-makers to more accurately and more confidently make the appropriate decisions and recommendations in response to a given tropical cyclone warning.

It is difficult for most people to directly relate an advertised wind speed – a numerical value – to its potential for causing damage. Numerous questions come to mind. For example: What kind of specific damage would a 120-mph typhoon cause? What kind of wave action would a 150-mph typhoon produce in a bay or across a reef? At what wind speed would a tin roof blow off? At what wind speed would a car flip over? At what wind speed would waves wash away coastal houses? At what wind speed would concrete power poles sustain damage or blow down? If the answers to these and similar questions are known ahead of time by the emergency managers, they can more accurately tell the general public what actions to take in response to the predicted winds. They can also more specifically address questions that the general public may have regarding a given tropical cyclone situation. The scale can also be used by the media to give the public a more accurate idea of a typhoon's specific damage potential.

A secondary use of the scale is to assist in a post-storm assessment of the winds experienced at a location based on an analysis of the level of damage, especially where wind measuring equipment is not available or was inoperable. This application should only be used by meteorologists, weather observers, or damage assessment officials, who are adequately trained in discerning the relationship between specific types of damage and the winds that would likely produce that level of damage. This *User's Manual* does, however, provide some guidance for using the scale to estimate the wind speed from the observed damage.

The scale employs the basic structure of the Saffir-Simpson Hurricane Scale (SSHS) (Saffir 1972,1975; Simpson 1974), which has been used in Atlantic and Gulf Coast regions of the United States for over two decades. In these regions, the SSHS has taken on the importance for hurricanes that the Richter Scale has taken on for earthquakes in earthquake-prone areas. The innovative SSHS was devised in 1971 by Mr. Herbert Saffir, a Miami, Florida-based engineer, who developed the scale for the United Nations. He later gave the scale to the National Hurricane Center (NHC) in Miami. Dr. Robert Simpson, then the Director of the NHC, added the storm surge information to the SSHS. While the SSHS has been used very successfully in the United States, it has not been applicable to the tropical Pacific (OFCM 1995; Saffir 1993).

Since 1991, Guard and Lander have carefully studied and catalogued numerous cases of tropical cyclone wind damage in the tropics and subtropics. After assessing many available wind-damage scales (e.g., Amadore 1982, Fujita 1971, etc.), the authors decided to adapt the parameters of the SSHS for use in tropical island environments. The adaptations are based on the assessments of damage as revealed by hundreds of damage photos, personal observations, tropical cyclone summaries (e.g., JTWC 1980-1996), post-cyclone damage reports, and interviews. Initially, the authors looked at only western Pacific cyclones. Later, tropical cyclone damage in other tropical basins was examined, and the scale was generally found to apply equally across all the tropical basins. The authors also expanded the scale to include a tropical storm scale, since sub-hurricane force winds were found to cause significant damage on less-developed tropical islands. Earlier versions of the wind scale were presented at the 20th Conference on Hurricanes and Tropical Meteorology, 10-14 May 1993, at San Antonio, Texas (Guard and Lander 1993), and at the Fourth World Meteorological Organization (WMO) International Workshop on Tropical Cyclones (IWTC-IV), at Haikow, China from 21-30 April 1998 (WMO 1998). This new tropical cyclone scale has been coined the Saffir-Simpson Tropical Cyclone Scale as recommended by Mr. Herbert Saffir. We havd given the Saffir-Simpson Tropical Cyclone Scale the acronym STCS, which is pronounced STICKS.

A scale that relates the force of various tropical cyclone winds to the potential damage to structures, vegetation, and coastal zones has long been needed in the tropical Pacific Ocean. Tropical cyclone warnings issued by every regional warning agency contain current and forecast estimates of the maximum sustained winds for a given cyclone. Despite this specific information, in many cases, emergency managers and the general public do not understand the relationship of these numerical wind values to the potential damage and risk to themselves, their property, and their immediate environment. As a result, even a perfect warning often does not elicit the desired response by the public or by emergency managers, placing lives and property at unnecessary risk.

STCS ("sticks") is specifically adapted for the tropics. It considers the construction materials and building practices that are common to the tropics. It incorporates the harshness of the tropical environment by considering the weakening effects of termite infestation, wood rot, and salt-water and salt-air corrosion. STCS also identifies the wind damage to tropical trees. Finally, STCS accounts for the unique effects of coral reefs on coastal wave action, storm surge, and coastal inundation or wave run-up from the impinging wind-driven waves.

STCS is divided into seven distinct wind categories: two categories encompass tropical storm-force winds and five categories encompass typhoon/hurricane-force winds. The five typhoon/hurricane categories use the identical wind ranges used in the SSHS. This allows comparisons among the many hurricane basins. A brief discussion of the behavior of tropical storm and typhoon winds over land and water, and the effects of storm-generated waves around coral islands and coastlines are provided in subsequent sections. Finally, some guidance for using the scale to estimate wind speeds from observed damage is discussed.

This *User's Manual* is divided into nine sections. Section 1 is this Introduction. Section 2 discusses the assumptions that are made in developing STCS and the methodology used in producing it. Section 3 summarizes the basic parts of STCS, including the wind-damage categories, the sustained and gust wind speed ranges, the potential over-land damage, and the potential coastal wave action and coastal inundation. This section of the manual will likely be the most used portion. Section 4 discusses some of the behavioral characteristics of over-land and over-water winds. In this section, we also illustrate the differences in the characteristics of winds that occur from a near miss, a partial eye passage, and a complete eye passage. Section 5 discusses the effects of the coral reefs on the incoming waves and on the coastal inundation. Here, some attention is also given to the behavior of the waves at cliffs that rise vertically from the deep ocean. Section 6 provides information on wind damage to various types of structures and infrastructure found in the tropics. Examples of typical kinds of damage and the categories of wind producing it are expounded upon. Section 7 provides information on wind damage to various types of tropical trees. Here, trees are categorized into basic types based on their characteristic responses to tropical cyclone winds. Section 8 provides guidance for the application of STCS. This section is designed to be used with the information in the previous sections. Section 9 summarizes the User's Manual with a quick reference table that relates tropical cyclone wind category to wind speed ranges and coastal inundation ranges. Some additional technical information is provided in the Appendixes. Appendix A provides a table for converting 1-minute wind speeds to 10-minute wind speeds. Appendix B is a list of tropical trees, giving the local (Chamorro) name, the common name, and the scientific name (genus and species), the scientific family name, and the tree-type based on their characteristic responses to tropical cyclone winds. Appendix C shows a "quick-reference" wind-damage table that was produced for Guam using the parameters from STCS. Similar "quick-reference" tables can be developed for other locations. Appendix D shows the relationships between maximum tropical cyclone wind speed and minimum central pressure. Appendix E is the scale currently used in the Atlantic Ocean—the Saffir-Simpson Hurricane Scale (SSHS). There is also a list of acronyms.

2. ASSUMPTIONS AND METHODOLOGY

2.1. Assumptions and pertinent facts

Several assumptions were made in the development of STCS. These assumptions are:

(1) Maximum sustained winds refer to those tropical cyclone wind speeds expected over water. While terrain can significantly modify the winds, over-water winds are most representative of the maximum sustained winds over small, flat islands or at coastal areas where a tropical cyclone moves ashore.

(2) The potential peak gust over land is virtually the same as the potential peak gust over water. For this reason, it is desirable to obtain the peak gust and derive the sustained wind from the peak gust. A 1-minute or a 10-minute wind can be derived from the peak gust using empirically derived relationships.

(3) For United States-affiliated locations, a version of STCS is used in which the maximum sustained winds are based on a 1-minute average wind speed. For other locations, the maximum sustained winds should be based on a 10-minute average wind (about 14% less than a 1-minute average over-water wind). The potential peak gust for a given 1-minute average sustained wind is the same as the potential peak gust for the corresponding 10-minute average sustained wind.

(4) The minimum sea level pressure in the center of the tropical cyclone is not given as part of STCS. This is a deviation from the SSHS, which does display pressure values in the scale. While there is a general relationship between the minimum central pressure and the maximum sustained wind, there are significant deviations that can result in a considerable under- or over-estimate of the wind speed. These deviations are especially prevalent in the western Pacific (Callaghan and Smith 1998). The relationships between maximum wind and minimum pressure are briefly discussed in Section 4 and in Appendix D.

2.2. Methodology

The authors, having spent a total of nearly 20 years at the Joint Typhoon Warning Center (JTWC) when it was located at Nimitz Hill, Guam[1], have directly or indirectly observed the effects of nearly 2,500

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[1] The Joint Typhoon Warning Center was located at Nimitz Hill, Guam from May 1959 until January 1999 when it moved to Pearl Harbor, Hawaii.

tropical cyclones. They have directly experienced the effects of over 75 tropical cyclones, including 10 eye passages. Initially, the data relating the maximum observed wind and the resulting damage from tropical cyclones personally observed by the authors were put into a general knowledge base as suggested by Sheifer and Ellis (1986). This knowledge base was then compared with several existing wind-damage scales (e.g., Simpson 1974, Fujita 1971, Amadore 1982, etc.). After a careful assessment of these scales, it was determined that the Saffir-Simpson Hurricane Scale (SSHS) used in hurricane-prone regions of the United States provided the best delineation of wind-damage categories for hurricane-force winds. That is to say, significant increases in the level of damage in the observed tropical regions fit very nicely into the existing Saffir-Simpson hurricane wind categories.

Next, the authors studied hundreds of photographs and official reports of tropical cyclone-induced damage that occurred in western North Pacific tropical and sub-tropical regions. The damage to tropical vegetation was studied carefully, and in many cases, the trees were found to be a very good indicator of maximum wind speed. This knowledge was important where maximum wind speed could not be ascertained from the damage to structures or because wind-measuring devices were inoperative, damaged, or destroyed. For example, in some cases, construction of dwellings was so poor that damage was total even in the lower hurricane wind categories. In other cases, landfall occurred in sparsely populated areas where the damage to structures could not be used exclusively to determine the wind speed. Initially, the concurrent JTWC tropical cyclone "best track" intensity values were used to validate the wind speeds. However, where it was possible, the tropical cyclone "best track" intensity values were reassessed/reanalyzed for accuracy, and were changed where additional data justified such changes. Many of the techniques used to revalidate the wind data are described in Powell and Houston (1996a, 1996b) and in Fujita (1992). The World Meteorological Organization (WMO) Tropical Cyclone Secretariat in Manila provided numerous amounts of information, including landfall reports for many Asian countries that were invaluable to this reanalysis process. Appropriate changes were made to the best track maximum wind values as a result of the reassessments. In addition, scores of interviews were conducted to assess the level of damage from specific cyclone events of interest. This was primarily done following cyclones on Guam, on other Micronesian islands, and in the Philippines. All of this additional information was then used to construct STCS. During preparation of the scale, it became evident that on many tropical islands considerable damage could occur from sub-hurricane force winds. As a result, two tropical storm categories were developed. STCS was then tested against damage from more than 50 subsequent tropical cyclone events. Further fine-tuning was performed where necessary.

Following the initial assessment, the authors acquired damage photos and landfall reports from the tropical regions of other ocean basins. The damage response to the wind was found to be virtually identical in all of the world's tropical areas prone to tropical cyclones. Special rules were developed concerning damage to trees. In some cases, the same kinds of trees had markedly different appearances depending on their past typhoon experiences. For example, the *Delonix regia* [poinciana trees (flame trees)] in more equatorial areas that are seldom hit by typhoons are very tall and slender, and form a canopy over the tropical rain forests. Those poinciana frequently hit by typhoons, however, are much shorter, thicker-trunked, and stubbier, a result of continual loss of branches by the "pruning" effects of typhoons. In addition, the recovery of the vegetation after a tropical cyclone event was found to be dependent on the severity of the tropical cyclone winds and on the amount of rainfall following the event. Recovery was faster directly preceding the wet season than preceding the dry season.

An initial determination of the effects of storm surge, coastal wave action, and coastal inundation was also made from damage reports and observations. Storm surge, coastal wave action, and coastal inundation information were not as well documented as was the wind damage in the various reports. Of primary interest was the behavior of the ocean around and over fringing and barrier coral reefs. Unfortunately, the bathymetry and coastal reef morphology of the various locations were not always known. Observations of typhoon-induced waves and the behavior around and over the reefs of Guam and other Micronesian islands provided a great deal of the basis of the coastal wave action portion of STCS. Parametric wave models were also used to complement the observed data for wind-driven waves up to and across the reefs, and to determine the size of open ocean waves and swells. For wave heights across reefs, the value represents an average value over a 250- to 500-foot (76- to 152-meter) wide reef. Higher waves are seen to occur over narrower reefs -- less than 250 feet (76 m). For wider reefs (greater than 500 feet (152 m)), waves were found to be somewhat lower. Open bays that were drainage areas for rivers were found to allow wave set-up in a manner similar to continental shelf areas, and ultimately, the wave height values in these open bays not directly protected by reefs were found to be similar to those indicated by the SSHS (Atlantic scale). Wave behavior with fringing reefs was studied to a much greater extent than the behavior over barrier reefs. Values inside barrier reefs are somewhat higher, depending on the distance from the reef front to the land and the depth of water inside the reef moat. Waves affecting sheer cliffs are not specifically addressed in STCS, but their behavior was studied and is discussed in Section 7.

2.3. Some general comments on STCS

The following paragraphs describe the two tropical storm categories and the five typhoon/hurricane categories of the Saffir-Simpson Tropical Cyclone Scale (STCS), and the ranges of wind that pertain to each category. The categories are based on a 1-minute average maximum sustained wind (MSW) and its corresponding 1-3 second peak gust. These values are given in miles per hour (mph) and knots (kt). Conversions of STCS wind categories for 10-minute average winds in miles per hour, knots, meters per second, and kilometers per hour are given in Appendix A.

Structures and infrastructure described herein are those commonly found in tropical and subtropical regions. The weakening effects of termite infestation, wood rot, and salt water/salt air corrosion are addressed in STCS. Examples and discussions of wind damage to structures and infrastructure are shown in Section 6. Coastal wave action and coastal inundation refer to effects in open bays fed by rivers and at coastlines surrounded by fringing reefs.

There are four wave ranges for each wind category of STCS. These represent wave heights at the fringe of the reef and entering the open bays, the breaking waves inside the open bays, inundation heights for waves moving over reefs from 250 to 500 feet (76 to 152 m) wide, and inundation heights produced by waves moving across reefs less than 250 feet (76 m) wide. These values are given in feet (ft) and meters (m), where 1 ft = 0.3048 m. The discussion of wave behavior is found in Section 5.

The local names of the tree types described in STCS are for Guam and the Commonwealth of the Northern Mariana Islands (Chamorro language). The scientific names (*Genus species*) are shown in the text and in Appendix B. The tree-type classifications that are categorized into specific types based on similar wind-response characteristics are defined in Section 7 and are also shown in Appendix B. In the text, the scientific name is followed by an italicized number in parentheses that indicates the type of tree classification. Scientific names for the trees were primarily obtained from Hargraves and Hargraves (1970), Cameron et al. (1983), Moore and McMakin (1979), and Raulerson and Rinehart (1991). While the species are often listed in this User's Manual, it is the Genus that most closely delineates the tree's response to the wind. In adapting STCS for a specific locale, the tree types should be converted to the more common plant names that pertain to the given Genus and local species. Local experiences with tree damage may indicate that some adjustment in tree-type classification is needed for that locale.

The information in STCS can be made into a "quick reference" table to quickly cross-reference the types of damage for selected infrastructure, structures, etc. with the associated given wind categories. This is well-suited for disaster management officials who have to make quick, yet accurate, decisions in an often changing environment. An example of such a table is shown in Appendix C.

3. THE SAFFIR-SIMPSON TROPICAL CYCLONE SCALE (STCS—pronounced STICKS)

The following paragraphs summarize the specific tropical storm and typhoon wind categories, and their associated wind speed ranges, potential damage, and coastal inundation and wave action. A more detailed description of the damage caused by tropical-cyclone winds, and the inundation and wave action caused by near and remote tropical cyclones, can be found in the sections that comprise the remainder of this document.

3.1. TROPICAL DEPRESSION AND TROPICAL STORM CATEGORIES

1) TROPICAL STORM CATEGORY A: WEAK TROPICAL STORM

MSW: 30-49 mph (26-43 kt)
Peak Gusts: 40-64 mph (33-56 kt)

Potential Damage - Damage done to only the flimsiest lean-to type structures. Unsecured light signs blown down. Minor damage to banana trees [*Musa spp. (2)*] and near-coastal agriculture, primarily from salt spray. Some small dead limbs, ripe coconuts, and dead palm fronds blown from trees. Some fragile and tender green leaves blown from trees such as papaya [*Carica papaya (2)*] and fleshy broad leaf plants.

Coastal Inundation and Wave Action - On windward coasts, sea level rise of less than 2 ft (0.6 m) above normal in open bays and inlets due to storm surge and wind-driven waves; breaking waves inside bays can reach 2-3 ft (0.6-0.9 m); less than 1 ft (0.3 m) over reefs. Rough surf at reef margin with moderately strong along-shore currents (rip tides) inside reefs.

2) TROPICAL STORM CATEGORY B: SEVERE TROPICAL STORM

MSW: 50-73 mph (44-63 kt)
Peak Gusts: 65-94 mph (57-81 kt)

Potential Damage - Minor damage to buildings of light material; major damage to huts made of thatch or loosely attached corrugated sheet metal or plywood. Unattached corrugated sheet metal and plywood may become airborne. Wooden signs not supported with guy wires are blown down. Moderate damage to banana trees [*Musa spp. (2)*], papaya trees [*Carica papaya (2)*], and most fleshy crops. Large dead limbs, ripe coconuts, many dead palm fronds, some green leaves, and small branches blown from trees.

Coastal Inundation and Wave Action - On windward coasts, sea level rise of 2-4 ft (0.6-1.2 m) above normal in open bays and inlets due to storm surge and wind-driven waves; breaking waves inside bays can reach 3-5 ft (0.9-1.5 m); 1-2 ft (0.3-0.6 m) over reefs. Wind-driven waves can inundate low-lying coastal areas below 1-2 ft (0.3-0.6 m) on windward locations where reefs are narrow. Very rough surf at reef margin with strong along-shore currents (rip tides) inside reefs.

3.2. TYPHOON AND SUPER TYPHOON CATEGORIES

1) TYPHOON CATEGORY 1: MINIMAL TYPHOON

MSW: 74-95 mph (64-82 kt)
Peak Gusts: 95-120 mph (82-105 kt)

Potential Damage - Corrugated metal and plywood stripped from poorly constructed or termite-infested structures and may become airborne. A few wooden, non-reinforced power poles tilted, and some rotten power poles broken. Some damage to poorly constructed, loosely attached signs. Major damage to banana trees [*Musa spp. (2)*], papaya trees [*Carica papaya (2)*], and fleshy crops. Some young trees downed when the ground is saturated. Some palm fronds crimped and bent back through the crown of coconut palms [*Cocos nucifera (1)*]; a few palm fronds torn from the crowns of most types of palm trees; many ripe coconuts blown from coconut palms. Less than 10% defoliation of shrubbery and trees; up to 10% defoliation of tangantangan [*Leucaena spp. (4)*]. Some small tree limbs downed, especially from large bushy and frail trees such as mango [*Mangifera spp. (9)*], African tulip [*Spathodea campanulata (9)*], acacia [*Acacia spp. (8)*], etc. Overall damage can be classified as minimal.

Coastal Inundation and Wave Action - On windward coasts, sea level rise of 4-6 ft (1.2-1.8 m) above normal in open bays and inlets due to storm surge and wind-driven waves; breaking waves inside bays can reach 5-7 ft (1.5-2.1 m); 2-3 ft (0.6-0.9 m) additional water across reef. Wind-driven waves may inundate low-lying coastal roads below 2-4 ft (0.6-1.2 m) on windward locations where reefs are narrow. Minor pier damage. Some small craft in exposed anchorages break moorings.

2) TYPHOON CATEGORY 2: MODERATE TYPHOON

MSW: 96-110 mph (83-95 kt)
Peak Gusts: 121-139 mph (106-120 kt)

Potential Damage - Several rotten wooden power poles snapped and many non-reinforced wooden power poles tilted. Some secondary power lines downed. Damage to wooden and tin roofs, and doors and windows of termite-infested or rotted wooden structures, but no major damage to well-constructed wooden, sheet metal, or concrete buildings. Considerable damage to structures made of light materials. Major damage to poorly constructed, attached signs. Exposed banana trees [*Musa spp. (2)*] and papaya trees [*Carica papaya (2)*] totally destroyed; 10-20% defoliation of trees and shrubbery; up to 30% defoliation of tangantangan [*Leucaena spp. (4)*]. Light damage to sugar cane [*Saccharum spp. (3)*] and bamboo [*Bambusa spp. (3)*]. Many palm fronds crimped and bent through the crown of coconut palms [*Cocos nucifera (1)*] and several green fronds ripped from palm trees. Some green coconuts blown from trees. Some trees blown down, especially shallow rooted ones such as small acacia [*Acacia spp. (8)*], mango [*Mangifera indica (9)*], and breadfruit [*Artocarpus spp. (9)*] when the ground becomes saturated. Overall damage can be classified as moderate.

Coastal Inundation and Wave Action - On windward coasts, sea level rise of 6-8 ft (1.8-2.4 m) above normal in open bays and inlets due to storm surge and wind-driven waves; breaking waves inside bays can reach 7-10 ft (2.1-3.0 m); water is about 3-5 ft (0.9-1.5 m) above normal across reef flats. Wind-driven waves will inundate low-lying coastal roads below 4-6 ft (1.2-1.8 m) on windward locations where reefs are narrow. Some erosion of beach areas, some moderate pier damage, and some large boats torn from moorings.

3) TYPHOON CATEGORY 3: STRONG TYPHOON

MSW: 111-130 mph (96-113 kt)

Peak Gusts: 140-167 mph (121-144 kt)

Potential damage - A few non-reinforced hollow-spun concrete power poles broken or tilted and many non-reinforced wooden power poles broken or blown down; many secondary power lines downed. Practically all poorly constructed signs blown down and some stand-alone steel-framed signs bent over. Some roof, window, and door damage to well-built, wooden and metal residences and utility buildings. Extensive damage to wooden structures weakened by termite infestation, wet-and-dry wood rot, and corroded roof straps (hurricane clips). Non-reinforced cinderblock walls blown down. Many mobile homes and buildings made of light materials destroyed. Some glass failure due to flying debris, but only minimal glass failure due to pressure forces associated with extreme gusts. Chain-link fences begin to blow down. Light cars begin to be moved and occasionally overturned; a few high-paneled vehicles (buses, vans, etc) blown over. Some unsecured construction cranes blown down. Air is full of light projectiles and debris. Major damage to shrubbery and trees; up to 50% of palm fronds bent or blown off; numerous ripe and many green coconuts blown off coconut palms; crowns blown off of a few palm trees; up to 10% of coconut palms blown down. Moderate damage to sugar cane [*Saccharum spp. (3)*] and bamboo [*Bambusa spp. (3)*]. Some large trees {palm trees [*Cocos nucifera (1)*], breadfruit [*Artocarpus spp. (9)*], monkeypod [*Samanea saman (7)*], mango [*Mangifera indica (9)*], acacia [*Acacia spp. (8)*] and Australian pines [*Casuarina spp. (5)*]} blown down when the ground becomes saturated; 30-50% defoliation of many trees and shrubs; up to 70% defoliation of tangantangan [*Leucaena spp. (4)*]. Some very exposed panax [*Polyscias spp. (11)*], tangantangan [*Leucaena spp. (4)*], and oleander [*Nerium oleander (11)*] bent over. Overall damage can be classified as extensive.

Coastal Inundation and Wave Action - On windward coasts, sea level rise of 8-12 ft (2.4-3.7 m) above normal in open bays and inlets due to storm surge and wind-driven waves; breaking waves inside bays can reach 10-15 ft (3.3-4.6 m); water is about 5-8 ft (1.5-2.4 m) above normal across reef flats. Wind-driven waves may inundate low-lying coastal roads below 6-10 ft (1.8-3.0 m) of elevation on windward locations where reefs are narrow. Considerable beach erosion. Many large boats and some large ships torn from moorings.

4) TYPHOON CATEGORY 4: VERY STRONG TYPHOON

MSW: 131-155 mph (114-135 kt)

Peak Gusts: 168-197 mph (145-170 kt)

Potential Damage - Some reinforced hollow-spun concrete and many reinforced wooden power poles blown down; numerous secondary and a few primary power lines downed. Extensive damage to non-concrete roofs; complete failure of many roof structures, window frames and doors, especially unprotected, non-reinforced ones; many well-built wooden and metal structures severely damaged or destroyed. Considerable glass failures due to flying debris and explosive pressure forces created by extreme wind gusts. Weakly reinforced cinderblock walls blown down. Complete disintegration of mobile homes and other structures of lighter materials. Most small and medium-sized steel-framed signs bent over or blown down. Some secured construction cranes and gantry cranes blown down. Some fuel storage tanks may rupture. Air is full of large projectiles and debris. Shrubs and trees 50-90% defoliated; up to 100% of tangantangan [*Leucaena spp. (4)*] defoliated. Up to 75% of palm fronds bent, twisted, or blown off; many crowns stripped from palm trees. Numerous green and virtually all ripe coconuts blown from trees. Severe damage to sugar cane [*Saccharum spp. (3)*] and bamboo [*Bambusa* *spp. (3)*]. Many large trees blown down {palms *(1)*, breadfruit [*Artocarpus spp. (9)*], monkeypod [*Samanea saman (7)*], mango [*Mangifera indica (9)*], acacia [*Acacia spp. (8)*], and Australian pine [*Casuarina spp. (5)*]. Considerable bark stripped from trees; most standing trees are void of all but the largest branches (severely pruned), with remaining branches stubby in appearance; numerous trunks and branches are sandblasted. Patches of panax [*Polyscias spp. (11)*], tangantangan [*Leucaena spp. (4)*], and oleander [*Nerium oleander (11)*] bent over or flattened. Overall damage can be classified as extreme.

Coastal Inundation and Wave Action - On windward coasts, sea level rise of 12-18 ft (3.7-5.5 m) above normal in open bays and inlets due to storm surge and wind-driven waves; breaking waves inside bays can reach 15-25 ft (4.6-7.6 m); water is about 8-12 ft (2.4-3.7 m) above normal across reef flats. Wind-driven waves may inundate coastal areas below 10-15 ft (3.0-4.6 m) elevation. Large boulders carried inland with waves. Severe beach erosion. Severe damage to port facilities including some loading derricks and gantry cranes. Most ships torn from moorings.

5) TYPHOON CATEGORY 5: DEVASTATING TYPHOON

MSW: 156-194 mph (136-170 kt)
Peak Gusts: 198-246 mph (171-216 kt)

Potential Damage - Severe damage to some solid concrete power poles, to numerous reinforced hollow-spun concrete power poles, to many steel towers, and to virtually all wooden poles; all secondary power lines and most primary power lines downed. Total failure of non-concrete reinforced roofs. Extensive or total destruction to non-concrete residences and industrial buildings. Some structural damage to concrete structures, especially from large debris, such as cars, large appliances, etc. Extensive glass failure due to impact of flying debris and explosive pressure forces during extreme gusts. Many well-constructed storm shutters ripped from structures. Some fuel storage tanks rupture. Nearly all construction cranes blown down. Air full of very large and heavy projectiles and debris. Shrubs and trees up to 100% defoliated; numerous large trees blown down. Up to 100% of palm fronds bent, twisted, or blown off; numerous crowns blown from palm trees; virtually all coconuts blown from trees. Most bark stripped from trees. Most standing trees are void of all but the largest branches, which are very stubby in appearance and severely sandblasted. Overall damage can be classified as catastrophic.

Coastal Inundation and Wave Action - On windward coasts, sea level rise of 18-30+ ft (5.5-9.1+ m) above normal in open bays and inlets due to storm surge and wind-driven waves; breaking waves inside bays can be 25-35+ ft (7.6-10.7+ m); water is about 12-20+ ft (3.7-6.1+ m) above normal across reef flats. Serious inundation likely for windward coastal areas below 15 ft-28+ (4.6-8.5+ m) elevation. Very large boulders carried inland with waves. Extensive beach erosion. Extensive damage to port facilities including most loading derricks and gantry cranes. Virtually all ships, regardless of size, torn from moorings.

4. SOME BEHAVIORAL CHARACTERISTICS OF TROPICAL CYCLONE-INDUCED WINDS AS THEY PERTAIN TO POTENTIAL DAMAGE

4.1. Some characteristics of tropical cyclone-induced winds

Figure 1 is a wind trace from Typhoon Paka (December 1997) as it passed over Guam. It shows the strong wind gust values in the eye wall and the large change in wind direction between the left and right portions of the eye wall. The winds associated with a direct eye passage are different in character than winds of comparable intensity from a storm that does not make a direct hit. The latter affects a location with relatively unidirectional winds; thus, structures and vegetation are generally subjected to winds on only one side, and the lee side is somewhat protected. Eye passage, however, brings with it, rapid changes in wind direction, which imposes torques that more greatly twist the vegetation and structures. Parts of structures that were loosened or weakened by the winds from one direction are subsequently severely damaged or blown down by the strong winds that suddenly hit from nearly the opposite direction. A partial eye passage can do considerable damage, but significantly less than a total eye passage. While the maximum sustained wind might be 120 mph (105 kt) during the partial eye passage, the cost of damage will not be equivalent to that incurred in a total eye passage of the same intensity. The cost of damage from a partial eye passage of a 120 mph (105 kt) typhoon would more closely be equivalent to that from a total eye passage of a cyclone with maximum sustained winds of 110 mph (96 kt) (depending on the size of the island being hit).

Since tropical cyclones are generally circular, an eye passage over a location exposes that location to approximately the maximum possible duration of destructive winds. In addition, the higher winds associated with the convectively-active eye wall region have higher wind gusts than those outside it. Friction at the Earth's surface causes the wind to slow down as the wind gets closer and closer to the surface. In general, the gap between the sustained wind and the peak gust widens as wind speed increases and as the wind moves over land. The gustiness effect is amplified over land where friction reduces the sustained wind but not the peak gust. This widens the gap between the peak and lull of gusts even more, creating strong negative pressure forces on lee-side corners of buildings that are especially damaging to sheet metal and wooden structures. The exposure to the strong winds also exposes roofs and the eaves of roofs to strong lifting forces. Once the roof is torn from a wooden structure, support for the walls is greatly weakened, and they often collapse. Over water, the *maximum sustained wind* is about 78-80 percent of the *peak gust* (Krayer and Marshall 1992; Atkinson 1974). For example, if the peak gust were 100 mph, the sustained wind would be 78-80 mph. Figure 1 also shows the pressure trace, illustrating how fast the pressure falls as the high-wind-core approaches and how fast it rises as the center passes.

Figure 2 illustrates the various modifications that might occur to the winds of an approaching cyclone as they interact with the terrain of a mountain island. Because of surface friction, the over-water and over-land winds increase with height from the surface to about 3,000 feet. As a result, winds at higher elevations (location A) are, in general, stronger than winds at lower elevations (locations B and C). At the coast, the *sustained wind* is virtually the same as that 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 is greater over rough terrain than over smooth terrain. In addition, winds that get funneled down narrow valleys (location D) or between tall buildings can be stronger than those over open terrain (locations B and C). Mountains and 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. Here, turbulence reduces the frequency of the potential peak gust. Finally, winds can accelerate rapidly up over cliffs and bluffs (location F), exposing the cliff line to significantly stronger winds than those initially hitting the lower part of the cliff (location (C)). Winds can also accelerate up and down hillsides, between buildings, and where highways cut

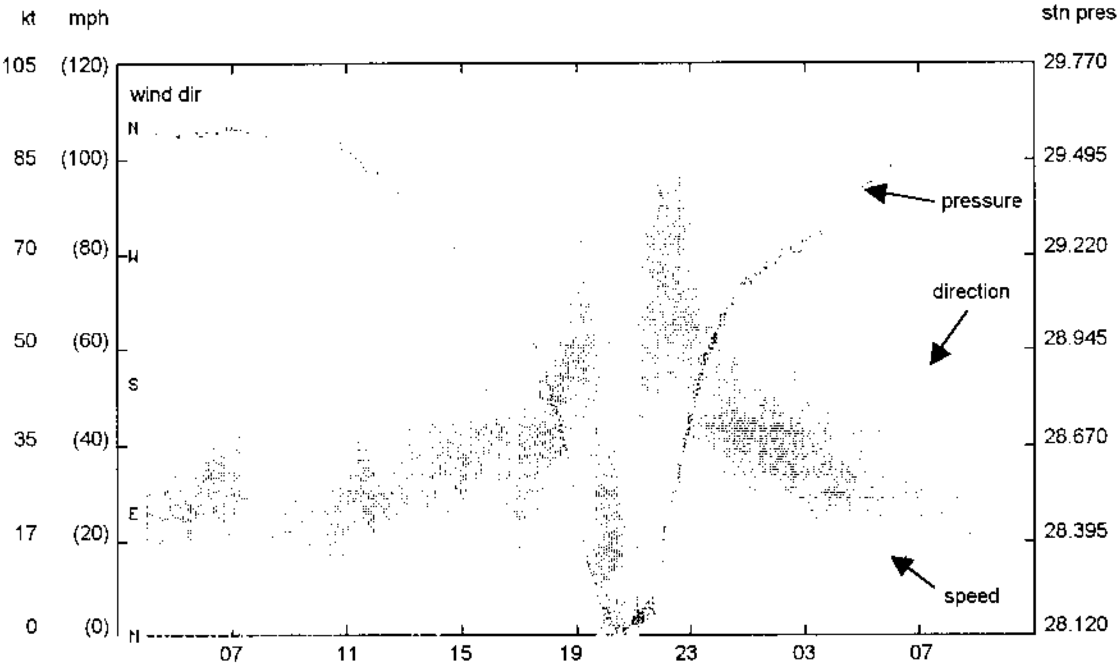


Figure 1. Wind and pressure trace of Typhoon Paka as it passed across Guam on 16 December 1997. The trace shows the wind gusts (red), wind direction (green), and the pressure (blue) measured at the Kuentos Communications site in Maite, Guam. Winds are in knots and miles per hour and the pressure is in inches of mercury. (Kuentos Communications, Inc.)

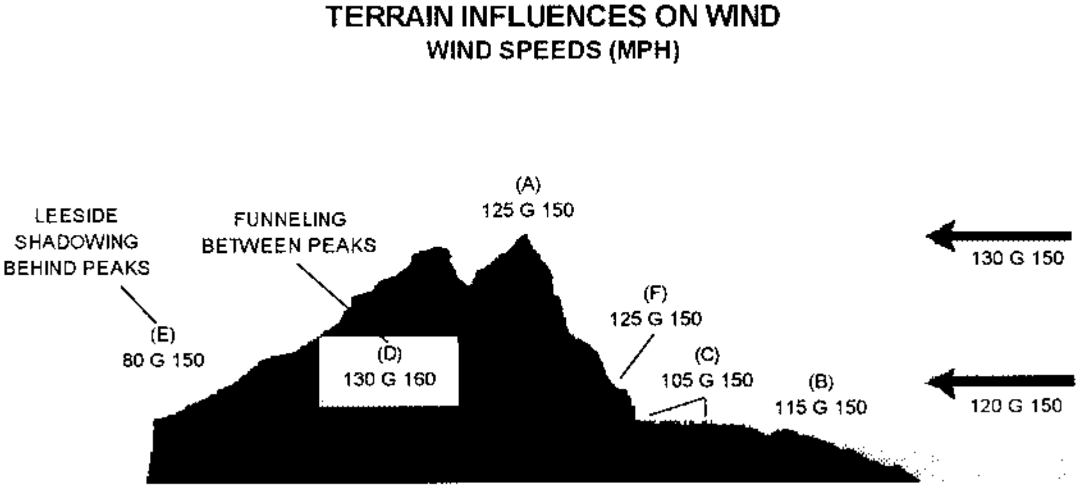


Figure 2. The effects of terrain on tropical cyclone winds. (A) represents a mountain peak, (B) a coastline, (C) an inland area at the base of a bluff, (D) a valley between mountain peaks, (E) an area shadowed by mountains or hills, and (F) top of a bluff or slope of a mountain. (Modified from Guard 1995)

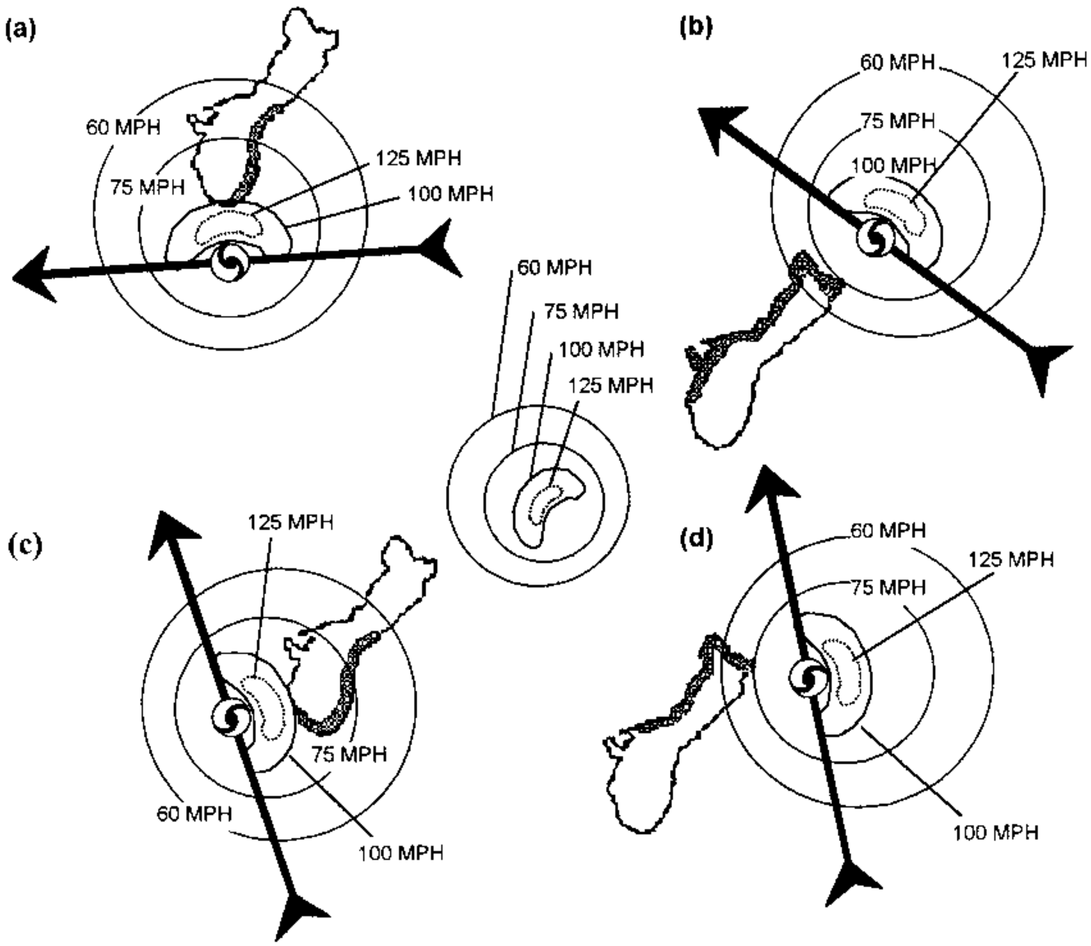


Figure 3. Relationship between movement of a tropical cyclone with respect to an island location and the maximum wind at that location for northern hemisphere tropical cyclones, as the cyclone passes (a) south, (b) north, (c) west, and (d) east of the island. Coastal shading indicates general coastal areas vulnerable to inundation.

through hills. Thus, for a given over-water wind, a variety of winds can be experienced over land, especially hilly or mountainous land. Despite the modification of the sustained winds by land, the *potential peak gust* over land is virtually the same as that over water. In the northern hemisphere (southern hemisphere), tropical cyclone near-surface winds rotate counter-clockwise (clockwise) around the center. If the tropical cyclone has little movement, the wind field around the cyclone is relatively symmetric. If, however, the cyclone is in motion, the speed of the movement, also known as translation speed, is added to the right (left) side of the storm with respect to its motion. Likewise, the speed of motion is subtracted from the left (right) side. This creates an asymmetric wind field with the strongest or "dangerous semicircle" to the right (left) side of the direction of motion. The "dangerous semicircle" has stronger winds and the destructive winds extend farther from the center.

Figure 3 shows the relationship between the track of a typhoon and the exposure of a northern hemisphere island to the weak or strong semicircle. The figure illustrates that if a northern hemisphere 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 tropical cyclone passes the same distance to the north (panel b). Similarly, if a northern hemisphere tropical cyclone passes to the west of a location (panel c), that location will be exposed to the "dangerous semicircle" and will receive stronger winds than if the tropical cyclone passes the same distance to the east (panel d).

Figure 4 shows the winds for a northern hemisphere tropical cyclone that approaches, passes over, and exits an island. Since a population or location generally experiences about 10 times more sideswipes or near misses than direct hits or eye passages, the level of destruction expected from a cyclone of a given intensity is often underestimated during an actual eye passage, the expectation of damage being based largely on past experiences. When an eye passage does occur, it is tantamount to getting hit by two back-to-back tropical cyclones. The total damage is significantly greater than that from the relatively unidirectional winds of a near miss with comparable wind intensity. While the specific degree of damage from winds of an eye passage is similar to that from the same intensity winds of a near miss, the eye passage produces much more widespread damage. That is to say, 100 mph (85 kt) sustained winds, whether from eye passage or a near miss, will damage or destroy the same kinds of structures (e.g., wooden), but the eye passage will damage or destroy many more of the same kinds of structures.

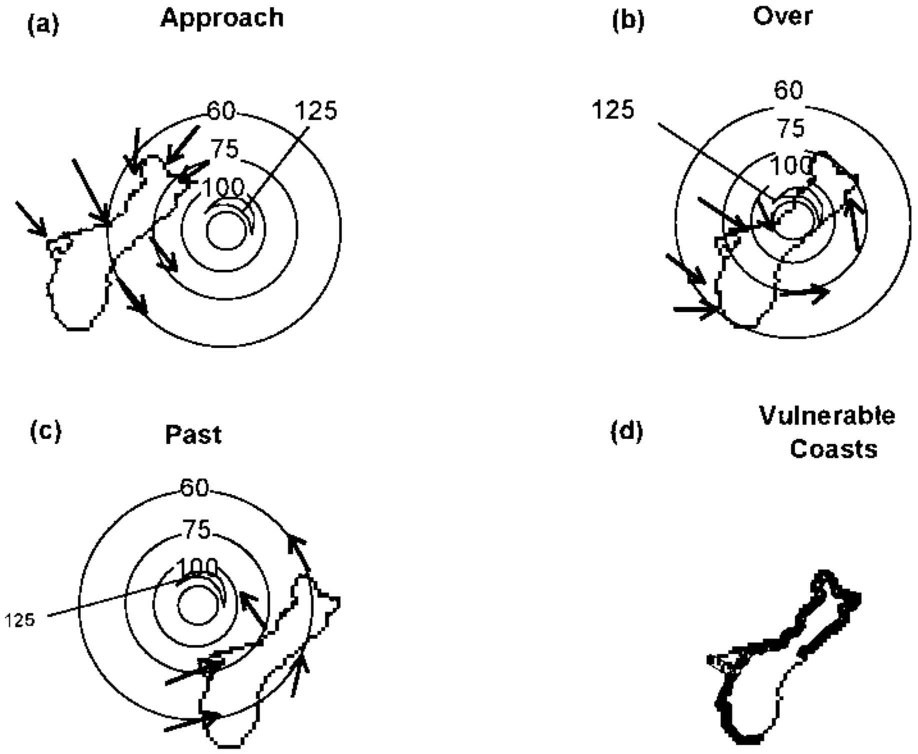


Figure 4. Winds for a northern hemisphere tropical cyclone making a direct hit on an island, as the tropical cyclone (a) approaches, (b) passes over, and (c) moves past the island. (d) shows the coastlines vulnerable to storm surge and inundation/wave run-up as a result of the path. (Modified from Guard et al. 1999)

5. WAVE AND STORM SURGE BEHAVIOR AROUND AND ACROSS CORAL REEFS

5.1. General information

Coral reefs that rise abruptly from deep water surround most tropical Pacific islands. They help protect the islands from the devastating effects of storm surge and coastal wave action that are observed in other parts of the world such as India, Bangladesh and the East and Gulf coasts of the United States. At these more continental locations, gradually sloping coastal shelves allow wave setup of elevated water levels that occur from wind-driven swells and waves, and from a dome of sea water induced hydrostatically by the cyclone's low pressure (more than 3 feet (1.0 m) above mean high tide levels for intense tropical cyclones) and by wind stresses on the ocean surface (Jelesnianski et al. 1992). These elevated water levels can affect windward coastal locations at distances up to 100 miles from the cyclone's eye wall.

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 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." The elevated mound of water is illustrated in Figure 5a. Figure 5b shows the components of storm surge in a coastal area with a continental slope (e.g., Bangladesh, the southeast US). Figure 5c indicates the components of storm surge in the environment of an island surrounded by a coral reef, and the effects of the reef to reduce the "conventional storm surge." Of significance is the ability of the reef flat to reduce the height of (dampen) the waves that flow across it.

The height of the seas and swells generated by a typhoon varies with the typhoon's intensity, size, speed of movement, and changes in direction of movement. Over the ocean, the combined effects of the elevated sea surface due to hydrostatic effects of lower atmospheric pressure near the eye and the very strong winds near the eye wall act to build a dome of water ahead of the typhoon and slightly to the right (left in the Southern Hemisphere) of its direction of motion (see Figure 5a). This elevated dome of water contributes significantly to the "storm surge" inundation in areas with a continental shelf. In areas surrounded by a reef, much of this water is deflected by the underwater portion of the reef. However, in localized areas, such as where the reef is narrow or cuts exist in the reef, the surge can lead to very large waves. **Because of all of the variables involved, it is highly recommended that specific island governments map the storm inundation characteristics of the island based on historical data.**

There are basically two types of tropical islands in which the coastal areas are protected by reefs: (1) low-lying atolls and (2) mountainous (so-called "high") islands of volcanic or tectonic origin (Myers 1991). The atolls generally have the greater protective reef area, however, since they lack substantial elevation (usually less than 10 feet (3.0 m)), they are at risk from even small amounts of inundation from the open ocean. They are also at risk from inundation from lagoon-side waters. Even 35 mph (30 kt) sustained winds blowing across a lagoon that persist for 24 hours or more can cause inundation from the lagoon waters. The high islands of the Pacific have more complex coastal areas consisting of reefs, bays, estuaries, rivers, and cliffs. The concave shape of the bays act to focus and funnel the rising waters toward the land. Rivers deposit silt in the coastal areas where they drain. The silt weakens or kills the coral, allowing water to erode the reef, and making the slope of the bottom flatter and more susceptible to wave setup. Flash flood waters from rivers and runoff into the bays during typhoons cannot easily escape to the open ocean and add to the level of the coastal waters and coastal flooding.

Most reefs have "cuts" where water is normally channeled from the reef flats back into the open ocean. Figure 6a is a cross section of the structure and characteristics of the fringing reef of a high Pacific island. Figure 6b shows a top view of the reef structure and characteristics. The reef flats may vary in width from a few feet to thousands of feet. As waves wash over the reef margin and move across the reef flats, strong currents (rip tides) develop parallel to the coast, moving water from the flats to the "cuts" and back to the open sea. The tremendous force and size of the of the waves created by a typhoon pile more water than normal onto the reef flats, and the forward force of the waves can slow or prevent the water's normal escape back through the "cuts" to the open ocean. When the force of the

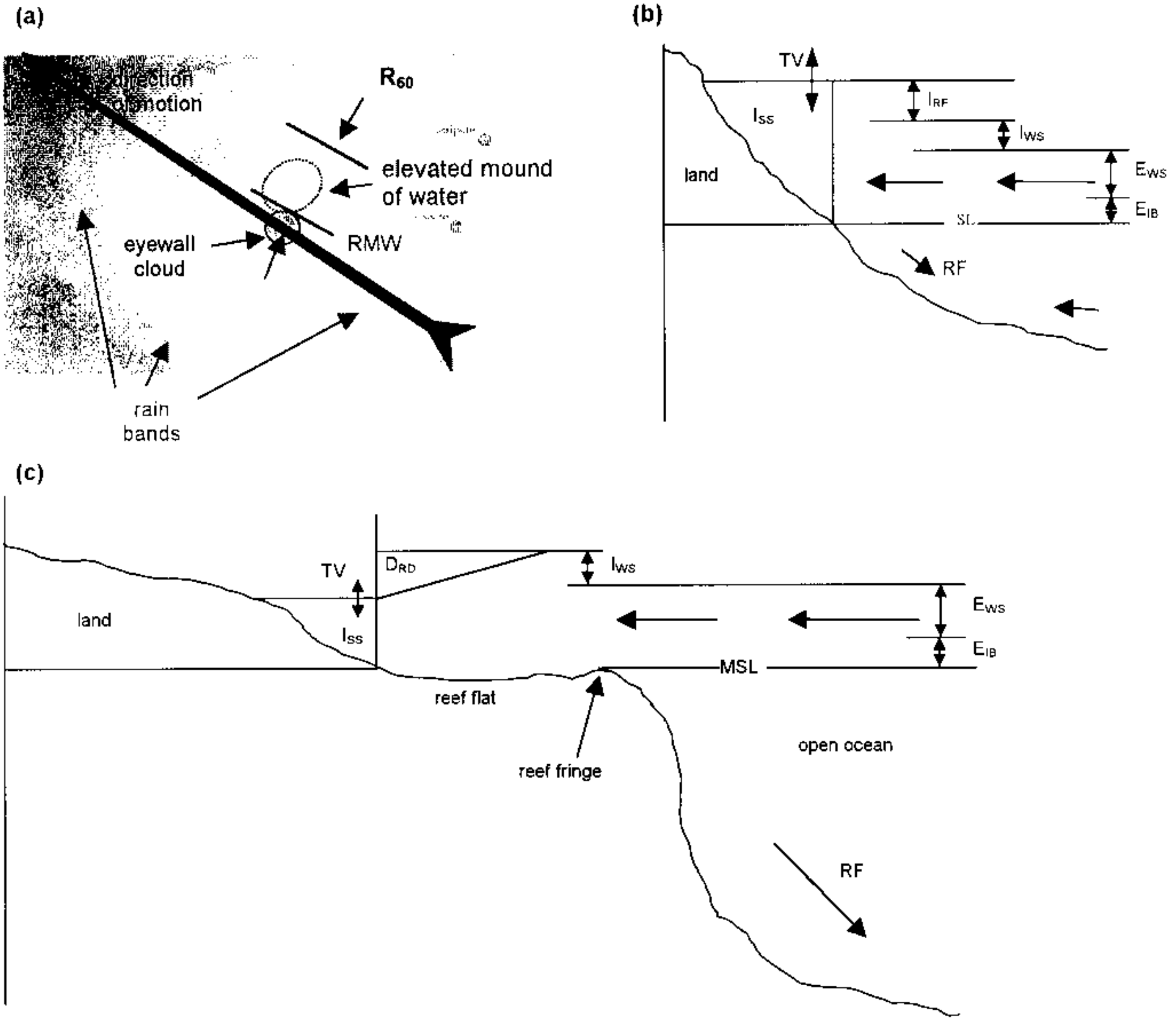


Figure 5. Conceptual models of the development of tropical cyclone-induced storm surge and inundation. (a) Diagram showing the elevated mound of water due to wind stress and the inverse barometer effect in relation to the typhoon's eye, eye wall cloud, direction of movement, radius of maximum wind (RMW), 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_{IB} 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.

waves gets strong enough, the return flow to the ocean, through the "cuts," can slow down considerably, allowing water levels to build up in the coastal areas. When the force of the incoming waves gets strong enough, the "cuts" can act as funnels, channeling massive volumes of water from the ocean toward land, in addition to the volumes breaking over the reef flats. It is this wind-driven wave setup of high water above the level of the reef margin that constitutes the "storm surge" at locations with extensive reefs.

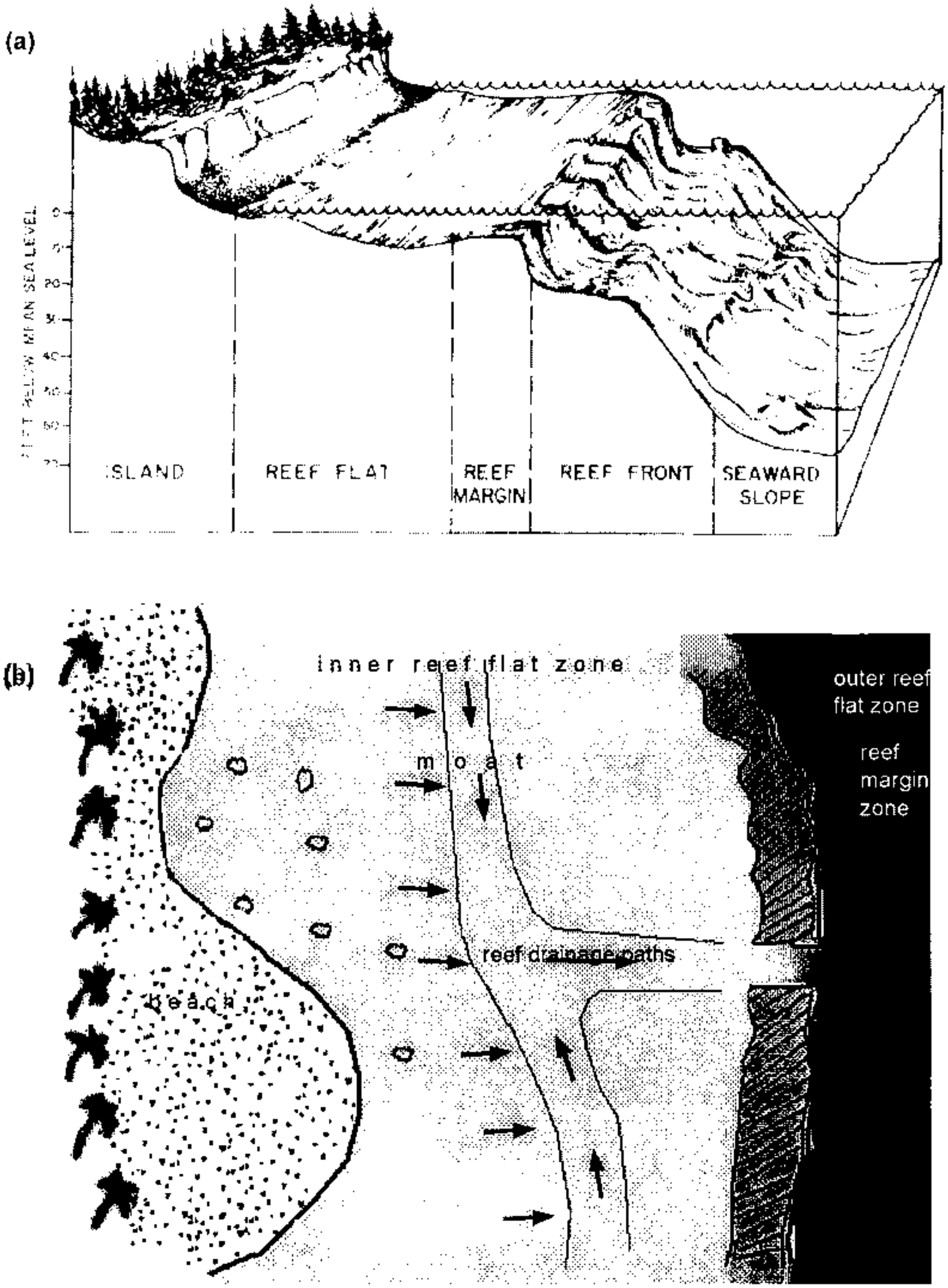


Figure 6. (a) 3-D side view and (b) planer top view of a coral reef, showing the reef structures that affect the characteristics of waves and the amount of inundation. ((a) modified from USNOO 1971 and (b) modified from Guard 1995.)

In the open bays and along reefs, the worst effects are felt where the direction of motion of the wind-driven waves is perpendicular to the mouth of the bay or the edge of the reef. Since the reef itself acts to decay or dampen the surge of water from waves, which break at the reef margin, potential inundation is greatest where the reef flat is narrow. The oceanic effects of a typhoon at a specific location are dependent on many factors. Some of these factors include the variation of the normal astronomical tides, the slope of the bottom topography seaward of the reef margin, the presence of cliffs or bays, the width of the reef flats, the angle of the wind-driven waves to the cliffs/reefs/bays, and the presence of points or peninsulas that may deflect the oncoming water from the entrances of the bays and estuaries.

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., ≥ Typhoon Category 3 on the Saffir-Simpson Tropical Cyclone Scale) over an island or coastal area is usually accompanied by large to phenomenal waves on all windward shores exposed to the high winds in and near the eye wall. The direct eye-passage scenario and the vulnerable coastal areas for a northern hemisphere island are shown in Figure 4.

When the eye of the typhoon passes close to a location, the winds in the core 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 an island during the eye passage. Here, intensity is important for the generation of wind-driven waves.

As waves hit the base of a cliff, they are similar in height to the waves generated in the open ocean. As the waves crash against the cliff, water is forced up the face of the cliff and may reach heights more than twice the height of the waves hitting the base of the cliff. Sheets of sea spray can reach heights more than four times the height of the waves hitting the base of the cliff (Lander and Guard 1997).

In general, large tropical cyclones, where winds blow over much longer distances across the ocean waters, will produce much larger and more powerful waves than small storms of comparable intensity and speed of motion. In addition, faster moving storms tend to produce larger and more powerful waves than do slower moving storms of comparable size and intensity. The latter effect is most pronounced as the typhoon speed of motion nears 20-25 mph (17-22 kt). However, slower moving storms allow the strong winds to spend more time over a location, producing more wind damage.

Typically, the coastal effects from swells emanating from typhoons can begin to be felt when the typhoon is still several hundred miles away. A storm can pass far enough away from a location not to produce destructive winds there, but still affect the location with destructive swells and waves. As a typhoon approaches to within a few hours of landfall, the maximum oceanic effects are encountered from the storm surge (primarily from the inverse barometer effect) and wind-driven waves from the intense winds at and near the radius of maximum wind.

Even 24-hour hurricane and typhoon track forecasts are frequently as much as 6 hours in error in predicting the time of landfall. At many tropical locations, this is the time period between a high and a low tide. Thus, coastal evacuation decisions should be based on the assumption that the arrival of the peak storm-induced oceanic effects will occur at high tide. Since 24-hour hurricane and typhoon intensity predictions in the western Pacific can be in error by as much as 30-40 mph (25-35 kt) and occasionally by as much as 85 mph (74 kt), evacuation decision-makers should strongly consider planning for a cyclone with an intensity one-half to one wind category higher than that forecast.

5.2 Specific effects

Tropical cyclone-generated waves and the resulting inundation can do considerable damage, and in many places the water kills many more people than the winds. Tens-of-thousands of people have been killed from the waves and storm surge that moved over coastal and river delta areas of India, China, and Bangladesh. Plate 1 shows several examples of coastal wave action and inundation on islands surrounded by coral reefs, and the resulting property damage and coastal erosion.

The Plate 1, upper left picture shows waves rolling in across a coral reef. Noting the stillness of the palm fronds, one can assess that the typhoon generating the waves is some distance away. The center was actually about 200 miles (321 km) away. The waves produced on the island by this typhoon were equivalent of those expected of a TY CAT 4 storm at eye passage. The haze is from the crashing of the waves against the cliffs and rocks.

The Plate 1, upper right picture shows the extent of typhoon-induced inundation. TY CAT 4 winds produced waves in the general area about 15 feet (5.0 m) high across 300-ft (91 m) wide reefs and up to 30 feet (9.1 m) high where the reefs folded in much closer to the coast. The confluence of the larger waves and the smaller waves produced inundation levels of different heights along the coast.

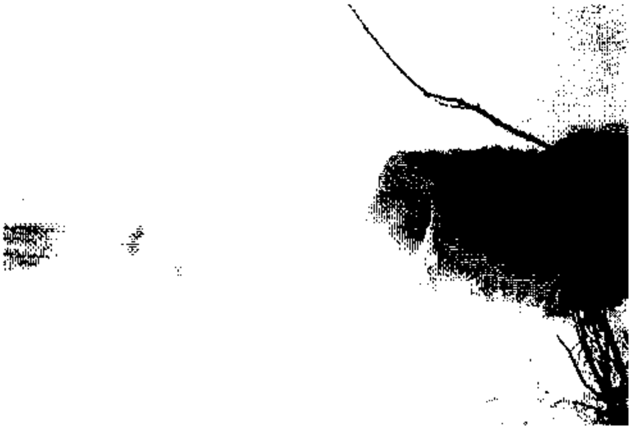
The Plate 1, middle left picture shows coastal erosion from large waves moving across a wide reef at high tide. The remotely-generated waves produced by this typhoon (when the typhoon was about 225 miles (362 km) away) were equivalent of those expected of the direct passage of a TY CAT 4 storm. The fallen palm tree at the left side of the picture was undermined by the incoming waves.

The Plate 1, middle right picture shows the result of inundation by waves travelling across a reef unto normally dry land. These waves were produced by a TY CAT 3 storm. The waves eroded the sand, exposing old coral heads. This coastal wave action was also responsible for destroying the pipes associated with a sewage out-fall.

The Plate 1, lower left picture shows the effect of large incoming waves crashing into other large waves that have reflected off the high coastal cliffs (which emanate from deep water). The large waves hitting a cliff can ride up the face of the cliff to heights twice that of the open ocean wave heights. In strong, inland blowing winds, the heavy spray from the breaking waves can be carried to heights four times the height of the open ocean waves. The heavy spray can be carried more than 3,000 feet (1 kilometer) inland.

The Plate 1, lower right picture shows part of the aftermath of the storm surge and wave action from a TY CAT 3 storm. As the winds increase, the boat breaks its mooring, is carried inland over the rocks by the rising water, then is deposited inland inside the rocks, and gets caught by the rocks as the water rapidly recedes.

PLATE 1



6. SOME FACTS ABOUT DAMAGE TO STRUCTURES AND INFRASTRUCTURE

6.1. General Information

Much of this information was compiled from several years of observed typhoon damage by the authors, from hundreds of damage photos, and from numerous post-storm studies. Much of the information has been formally compiled in the Typhoon Vulnerability Study for Guam (Guard et al. 1999). Because the wind categories constitute a fairly large range of winds, we often discuss a narrower range of winds in the category by appending "low-end", "medium", or "high-end" to the specific category.

6.2. Structures

Tropical cyclone-prone tropical regions provide a harsh environment for most buildings, structures, and facilities. Wooden structures are especially susceptible, being vulnerable to termite infestation, wood rot, and recurring strong wind events. Metal construction materials, such as hurricane ties, nails, screws, and window frames are susceptible to corrosion from salt spray and salt-laden air. Sheet metal buildings are susceptible to the corrosion problem, and also to joint separation by recurring strong winds and by expansion and contraction due to the intense tropical sun.

Concrete structures hold up much better in the tropics, but they are relatively expensive and require air conditioning. Hollow-block structures are more vulnerable to damage than structures made of concrete-filled hollow-block with structural steel bars (rebar) or steel-reinforced solid concrete. Rebar used to tie down the roof must be of sufficient gauge to prevent uplift of the roof. Steel-reinforced concrete roofs are the most typhoon resistant, but they are expensive and hot. For these reasons, structures with concrete walls often have wood and tin roofs. These roofs deteriorate with time. Even with fully concrete structures, windows and doors are vulnerable to strong winds and wind-blown debris. Well-engineered typhoon shutters can withstand winds at least up to high-end TY CAT 4 intensity.

Wooden structures or concrete structures with wooden roofs can be built to withstand winds up to high-end TY CAT 4 or low-end TY CAT 5, but they deteriorate with time. After 15 years with poor maintenance or 20-25 years with good maintenance, these houses may not hold up to low-end TY CAT 3 winds. Fully-concrete structures will likely hold up to any typhoon-force winds, but doors and windows will fail in stronger winds, and structural damage can occur from large debris (e.g., cars).

Sheet metal structures are common in the tropics, and can be built to withstand low-end TY CAT 5 winds, but like wooden structures, they deteriorate with time. Joints where the metal sheets are joined to each other or to the roof eventually separate, allowing wind to get under the metal. When this occurs, the flapping sheet metal can cause the steel frame of the structure to twist when winds reach high-end TY CAT 3 intensity. Many of the sheet metal buildings do not have sufficiently strong studs and braces between the structural steel supports, and strong winds can buckle the metal when the braces fail.

When winds reach high-end TY CAT 3, cars, buses, other vehicles, and shipping containers become vulnerable to blowing over; when winds reach low-end to medium TY CAT 5, vehicles and containers can become airborne. Parking lots, especially near large buildings such as hotels, are locations where vehicle damage can be very large. A portion of the wind hitting the large building can be channeled outward and can flip large numbers of cars. Winds accelerating between buildings or through openings in buildings can also cause cars to flip and tumble.

6.1.1. Infrastructure

After any strong tropical cyclone, the most critical problem is frequently restoration of the water and waste water distribution systems. Often, this requires restoration of critical parts of the power generation and distribution systems. Communications are also critical for providing information to the local populace and for communicating assistance needs with more distant locations. Once typhoons reach TY CAT 3 intensity, damage rises substantially. And when winds reach TY CAT 5 intensity, the level of devastation rises very rapidly from the low end to the high end of the category, even in the most strongly built and developed areas. Even the strongest of port facilities, airport facilities, fuel and water storage tanks, high voltage transmission towers, etc. are vulnerable to heavy damage.

Wooden power poles are susceptible to termite infestation and wood rot. New, well-guyed wooden power poles (about 12" (30 cm) in diameter) can hold up to high-end TY CAT 4 winds, but after 20 years or so, they will succumb to TY CAT 1 winds. When one pole falls, two, three, or four adjacent poles are often dragged down with it. Concrete and steel poles hold up to the winds much better, but they are considerably more expensive. Unguyed hollow-spun concrete poles will begin to fail in high-end TY CAT 3 winds, while properly guyed hollow-spun poles can stand up to medium TY CAT 5 winds. In high-end TY CAT 3 and TY CAT 4 winds, the failure rate is 12-14 times higher for wooden poles than for hollow concrete poles. Solid concrete poles are the most durable, but are very expensive.

Many above ground communications networks are susceptible to damage when winds reach TY CAT 2. This is especially the case for secondary telephone lines. Microwave towers are susceptible to misalignment when winds reach TY CAT 2 as well. This can effect local telephone and cellular service as well as long distance service. Microwave and radio towers are susceptible to destruction when winds reach medium to high-end TY CAT 3 intensity. The amount of damage escalates as winds reach the TY CAT 4 range, with larger radio antennas becoming vulnerable to breaking or being blown down. Even large satellite communications dishes can be damaged when winds reach TY CAT 5 intensity.

At coastal locations and on many islands, government buildings and churches are often used as typhoon shelters. Most of the designated typhoon shelters are concrete buildings, but many of these have only wood and tin roofs. These will generally hold up to TY CAT 2 winds, but structures with concrete roofs are preferable when winds approach TY CAT 3 and stronger intensities. As the wind speed increases, the number of people needing shelter also increases, but the number of adequate shelters decreases.

In order to assess damage and to provide relief to the affected population, roads must be accessible. Coastal roads are vulnerable to damage from inundation/wave run-up, which can undermine road beds and strip away large sections of asphalt. Large waves can also deposit large boulders and lots of sand onto the roads, requiring heavy equipment for removal. In general, the most detrimental hazards to roadways are downed trees, power poles and lines, and debris. This becomes a serious problem when winds reach TY CAT 2 and a very serious problem when winds reach or exceed TY CAT 3. At the higher categories, debris removal and management become a very large part of the recovery effort.

For islands, ports and airports are critical for outside relief. Most major ports and airports can withstand winds up to TY CAT 3. Once winds reach TY CAT 3, large ships can run ashore, damaging reefs, spilling oil, and occasionally closing deep water channels. When winds reach TY CAT 4, they can damage major port facilities, and when they reach TY CAT 5, they can damage the largest derricks and cranes. The vulnerability of airport structures depends largely on the construction materials. When winds reach TY CAT 3 or stronger, loading docks (jet ways) and navigation aids become susceptible to damage. This damage can occur from both the wind and the flying debris.

The Plate 2, top left picture shows a well-built wood and tin structure totally destroyed. Winds over the area were high-end TY CAT 4, but the structure was more likely exposed to high-end TY CAT 3 winds due to sheltering from the dense palm forest. Loosely constructed tin and plywood structures are susceptible to heavy damage by even TS CAT B winds.

The Plate 2, top right picture shows a wooden structure with a wood and tin roof. The roof and windows were destroyed by medium TY CAT 3 winds. While wooden structures with wooden roofs can be built to withstand TY CAT 4 winds, wood rot, termite infestation, corrosion due to salt, and repeated exposure to strong winds can leave the house susceptible to TY CAT 2 winds within 15 years with poor maintenance and within 20-25 years with good maintenance.

The Plate 2, center left picture shows an old military Quonset hut. Historically, these buildings have held up well to winds up through TY CAT 4. This old Quonset hut was destroyed by high-end TY CAT 3 to low-end TY CAT 4 winds. Repeated exposure to strong winds, salt-laden air, and years of expansion and contraction of the metal from the hot tropical sun weakened the structure.

The Plate 2, center right picture shows the destruction of a highly exposed wooden structure by medium TY CAT 4 winds. The walls were completely torn from the foundation. In the foreground, a concrete support is visible where a street light once stood before being stripped from the four visible bolts.

The Plate 2, lower left picture shows two destroyed Samoan *fales* after exposure to high-end TY CAT 3 winds during Cyclone Ofa in 1990. A smaller, adjacent *fale* (upper left) with its roof tied down with cables survived the winds. Tin structures in the foreground were also destroyed.

The Plate 2, lower right picture shows two adjacent concrete block structures with wooden roofs. The roofs began to fail when winds reached high-end TY CAT 2 intensity, and total failures occurred at various times as the winds reached medium TY CAT 4 intensity.

PLATE 2

The Plate 3, upper left picture is of a steel-reinforced concrete house with a tile-covered concrete roof. Tile failure was from both wind and blowing debris, and occurred when winds reached medium to high-end TY CAT 3. The house had little damage despite enduring medium TY CAT 4 winds. The broken branch of the Australian pine in the foreground is typical of high-end TY CAT 3 damage.

The Plate 3, upper right picture shows a steel-framed hollow block building. The hollow block was thin (4-6 inch/10-15 cm) and not completely filled with concrete, and the reinforcing rebar was of small gauge. As a result, the roof separated from the walls due to the uplift of the strong wind, and the walls eventually toppled on to the car during winds of low-end to medium TY CAT 4 intensity.

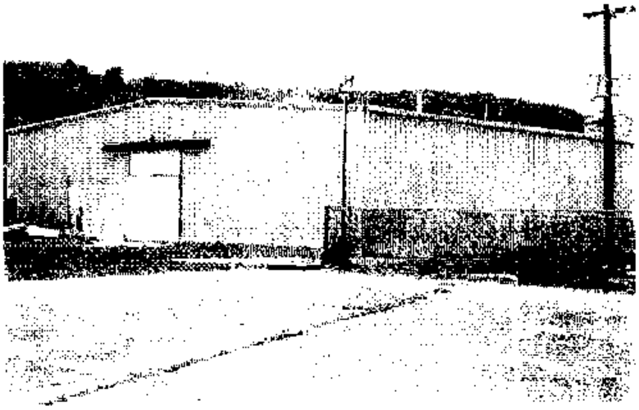
The Plate 3, middle left picture shows a well-built, steel-framed sheet metal warehouse. These structures are common in typhoon-prone areas. The weakest part of these structures are the doors, the joints where the roof meets the walls, and the joints where two separate pieces of siding are joined.

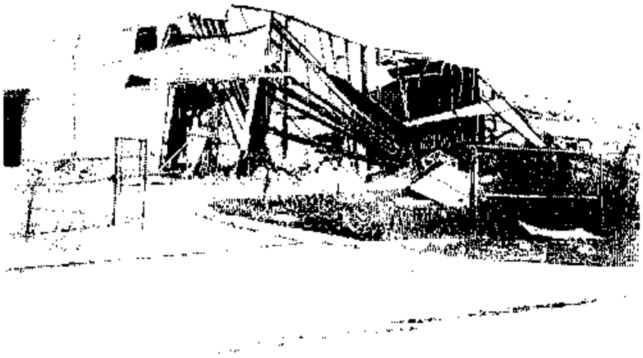
The Plate 3, middle right picture shows a relatively well-built, steel-framed sheet metal warehouse after exposure to low-end to medium TY CAT 4 winds. Note the light weight of the supports between the major frame supports. The steel frame was bent when the sheet metal was violently ripped from the structure.

The Plate 3, lower left picture illustrates what was then a recently built housing area that was subjected to the eye passage of Cyclone Tracy (Dec 1974) in Darwin, Australia. This devastation occurred from winds of at least medium to high-end TY CAT 4. This level of devastation cannot occur from TY CAT 2 winds as were estimated at the time (BOM 1997).

The Plate 3, lower right picture shows the failure of a wooden porch enclosure, the main back door, and a non-concrete storage room in an otherwise totally concrete housing unit. This destruction occurred during high-end TY CAT 3 winds.

PLATE 3





The Plate 4, upper two photos show aerial views of typhoon damage. The dense, wide-spread damage in the pictures is indicative of TY CAT 4 damage. In general, only concrete structures escaped the destruction. The structures in the photos were subjected to low-end (left) and medium (right) TY CAT 4 winds. An aerial view of TY CAT 3 damage would show similar heavy damage, but in smaller, less-widespread pockets.

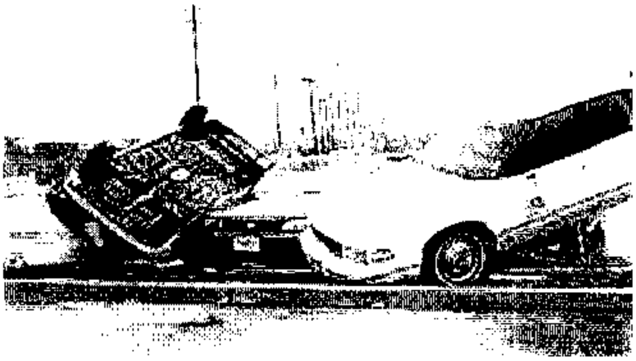
The Plate 4, center left photo shows toppled cars, a common occurrence in parking lots adjacent to the windward exposure of large buildings when winds reach medium to high-end TY CAT 3. When winds hit a large building, the air is forced up, down, and around the face of the building. The resulting localized wind becomes extremely turbulent, and the turbulent air currents can toss and turn the cars. Funneling between buildings or through openings in buildings can also displace and flip cars.

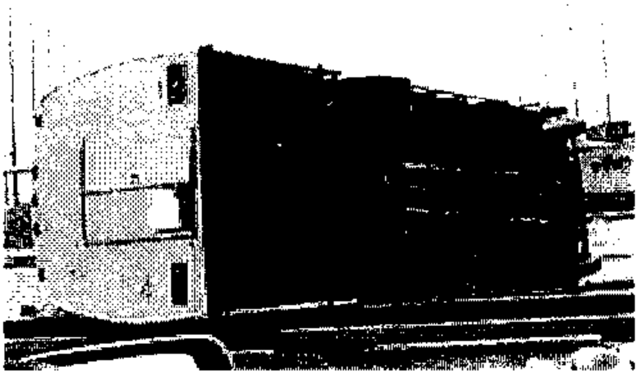
The Plate 4, center right photo shows a toppled bus. The high sides of buses, panel trucks, ambulances, and similar vehicles act as a sail, and despite their heavy weight, these vehicles can be overturned when winds reach high-end TY CAT 3 to low-end TY CAT 4 intensity.

The Plate 4, lower left picture is that of a mobile home. Mobile homes can survive strong winds if they are sheltered (in shallow valleys or not directly exposed to very strong winds) and are well-tied down with cables. The frail structures of mobile homes, even if tied down, will begin to buckle when directly hit by winds of high-end TY CAT 3 intensity.

The Plate 4, lower right picture shows a shipping container that has been converted into an office or living quarters. The container was not tied down. The heavy steel container was blown off its foundation and rolled by winds of high-end TY CAT 3 to low-end TY CAT 4 intensity. The large broken (mango) limbs to the right are typical of damage from these wind speeds.

PLATE 4





The Plate 5, upper left picture shows a downed wooden power pole. Survivability of wooden poles depends on the amount of termite infestation and wood rot, and whether or not the pole is guyed. The power lines act to guy the poles in two directions, but they need to be guyed in the directions perpendicular to the lines. When one poles falls, it frequently starts a chain reaction that drags a few adjacent poles with it. Weakened unguyed wooden poles can break in low-end TY CAT 1 winds, while relatively new, well-guyed poles can survive winds up to low-end TY CAT 5 intensity.

The Plate 5, upper right picture shows a damaged hollow-spun concrete power pole. Unguyed hollow-spun poles (12-14 inch (30-36 cm) base diameter) will begin to fail when winds reach high-end TY CAT 3 intensity. Up through high-end TY CAT 4 winds, the hollow-spun concrete poles have about 1/12th the failure-rate of wooden poles. Hollow-spun poles with larger diameter bases are less susceptible to failure. Solid concrete poles, while very expensive, can endure winds up to medium to high-end TY CAT 5 winds.

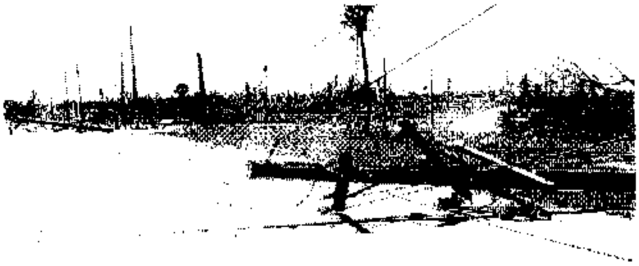
The Plate 5, center left picture (left frame) shows the survival of a hollow-spun concrete power pole and the simultaneous failure of a wooden pole. Winds were low-end TY CAT 3 intensity. The right frame shows a radio transmitting antenna after being subjected to low-end TY CAT 4 winds.

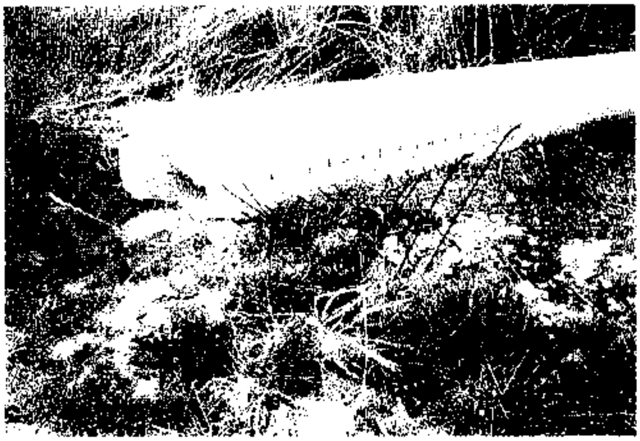
The Plate 5, center right photo shows damage to microwave transmitting towers. This occurred during high-end TY CAT 3 to low-end TY CAT 4 winds. Microwave towers can be blown out of alignment when winds reach TY CAT 2 intensity.

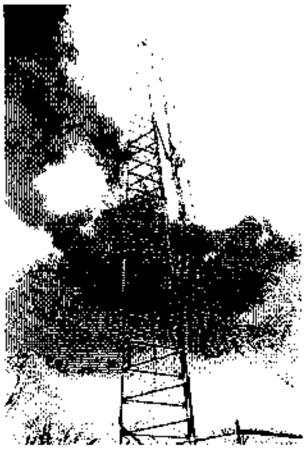
The Plate 5, lower left picture shows destroyed satellite ground stations subjected to medium to high-end TY CAT 3 winds. An antenna inside a well-built radome (not shown), just to the right of the downed antennas, escaped any damage and continued to operate during the entire period of the typhoon.

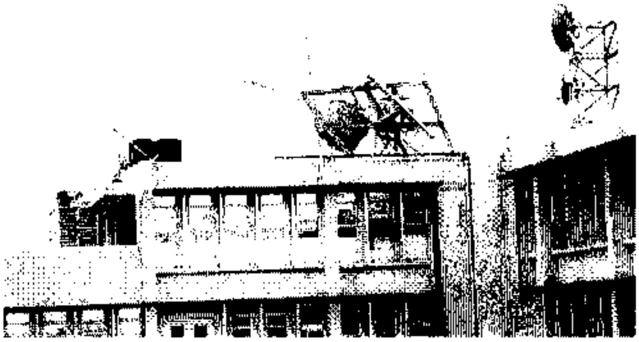
The Plate 5, lower right picture shows the damage to an empty fuel storage tank. The top was stripped from the tank and is seen lying to the right of the damaged tank. The damage occurred in high-end TY CAT 4 winds. Medium to high-end TY CAT 5 winds can damage partially full and full, well-maintained fuel and water storage tanks.

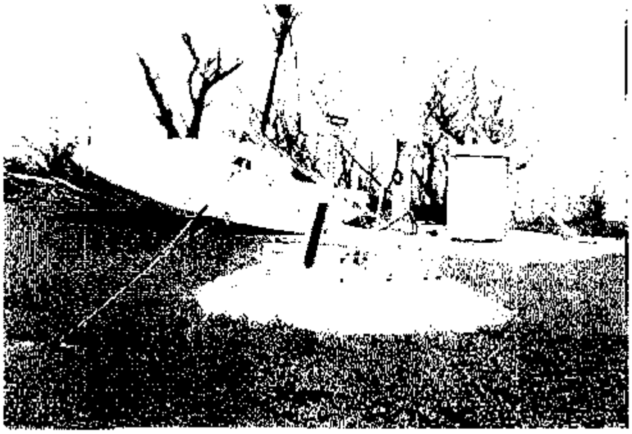
PLATE 5











7. TROPICAL CYCLONE WIND DAMAGE TO TREES

7.1. General comments

Trees are excellent indicators of tropical cyclone wind speed. After investigating hundreds of instances of damage to trees caused by tropical cyclone winds, the authors divided the trees into 12 specific types based on their characteristic responses to strong winds. These tree types were further fine-tuned using other studies describing tropical cyclone damage to trees (e. g., Cameron et al. 1983; Raulerson and Rinehart (1991)). Some of the trees may share characteristics of two adjacent types. This is especially the case with Type 8 trees. For example, the African tulip tree (*Spathodea campanulata*) has some characteristics of Type 9 trees (heavy defoliation) and the Yoga tree (*Elaeocarpus joga/sphericus*) has some characteristics of a Type 7 tree (strong trunk) and a Type 6 tree (resistance to uprooting).

7.2. Types of Tropical Trees With Respect to Response to Tropical Cyclone Winds

(Type 1) -- Palm trees -- Plants with tall woody trunks and a crown of radiating (palm) fronds. Palm fronds begin to crimp back through the crown when winds reach 65 kt/75 mph (low-end TY CAT 1) intensity; crowns begin to break from the top of the trunk (decapitate) when winds reach about 100 kt/115 mph (low-end to medium TY CAT 3). Coconut palms show a tendency to lean, and they begin to uproot when winds reach 100 kt/115 mph (low-end to medium TY CAT 3); tree falls are around 10% when winds reach around 105 kt/121 mph (medium TY CAT 3). Coconut palm trunks can also snap at these wind speeds, but falling is more common.

(Type 2) -- Banana/Papaya – Plants with a soft, fibrous, usually unbranched trunk and broad leaves. These plants begin to display damage with 50 kt/58 mph winds (medium TS CAT B) and are heavily damaged when winds reach 90 kt/104 mph (high-end TY CAT 2).

(Type 3) -- Bamboo/Sugar cane – Resists defoliation, but has a high propensity to lean in strong winds. Culms begin to lean when winds reach 90 kt/104 mph (high-end TY CAT 2) and begin to break when winds reach 110 kt/127 mph (high-end TY CAT 3); culms tend to break before they fall.

(Type 4) – Hedge acacia (Tangantangan)/Tamarind – A widely distributed tropical legume growing as a small scraggly tree with short branches and finely divided bi-pinnate leaves. There are 11-15 pairs of leaflets. This tree often grows in vast solitary stands. The tree tends to defoliate linearly with wind speed, beginning to lose leaflets after a few hours of winds at 65 kt/75 mph (low-end TY CAT 1) and becoming totally defoliated when winds reach around 130 kt/151 mph (high-end TY CAT 4). Leaflets are sensitive to salt spray and will brown and fall off in a few days, if not flushed with rain water.

(Type 5) -- Australian pine – Not a true pine, but a primitive flowering plant, growing as a pyramid shaped tree with horizontal branches bearing long, green, needle-like branchlets. Branchlets and small brittle branches begin to tear from trees when winds reach 50 kt/58 mph (medium TS CAT B). Young trees have a strong propensity to lean over when winds reach and exceed 100 kt/115 mph (low-end to medium TY CAT 3). They can uproot and large branches can break when winds reach or exceed 110 kt/127 mph (medium to high-end TY CAT 3). These trees often develop multiple trunks.

(Type 6) -- Banyan/Palomaria/Hibiscus/Fagot/Baobab -- Medium to large trees that are very stable in strong winds. Strength may come from aerial roots that emerge from the trunk and branches or from an extensive root system. Trees tend to resist defoliation but readily shed branches to reduce stress on the trunks. Little uprooting, significant leaning, or trunk breakage in winds up to 130 kt/151 mph (high-end TY CAT 4 to low-end TY CAT 5) is observed.

(Type 7) -- Flame tree/Monkey pod/Cassias/Eucalyptus – Medium to large trees with extensive but shallow root systems. Trees tend to shed leaves and large branches to reduce stress on trunks, and begin to uproot when winds reach or exceed 105 kt/121 mph (medium TY CAT 3) if ground is saturated. Surviving trees develop thick, stocky typhoon resistant trunks. Trunks are resistant to splitting and significant leaning.

(Type 8) -- Plumeria/Acacia/Albizia/African Tulip/Yoga/Ifil/Orchid/Coral/Cerbera/Talisai -- Small to large trees that readily shed limbs but generally resist defoliation in strong winds. Trees that survive TY CAT 3 or stronger winds tend to shed large, near ground-level branches and develop stocky, typhoon resistant trunks. Most have a high propensity to lean, and sometimes produce multiple trunks. Despite damage, these trees tend to recover rapidly.

(Type 9) -- Mango/Breadfruit/Pisonia/Ceiba/Kamachile/Erythrina – Small to large trees with shallow root systems and a high propensity for leaning, falling/uprooting (40-50% may fall when winds reach or exceed 120 kt/138 mph (low-end to medium TY CAT 4). Trees tend to shed leaves and branches to reduce stress on trunks, but trunks are susceptible to splitting. These trees begin to lose dead limbs when sustained winds reach about 44 kt/50 mph (TS CAT B) and small live branches when those winds make it to about 65 kt/75 mph (low-end TY CAT 1). They begin to lose large limbs when winds reach 90 kt/104 mph (high-end TY CAT 2). These trees also have a high propensity for developing multiple trunks.

(Type 10) – **Norfolk Island pine** – A tall pine with numerous short horizontal branches from which green stalks protrude, from the tip of the branch to the trunk. The stalks are surrounded by tightly packed, short, upward protruding pine needles, giving the appearance of a "cat tail". Young trees have flexible branches and tend to uproot in strong winds. As trees mature, the branches become stiff, and begin to break-off when winds reach 65 kt/75 mph (low-end TY CAT 1) intensity.

(Type 11) – **Mangrove/Oleander/Panax/Bougainvillea** – Bushy type trees, frequently with vertically extending branches rising from a common crown near the ground. The trees are very resistant to defoliation. They begin to lean when winds reach 105 kt/121 mph (medium TY CAT 3) and they begin to flatten or uproot when winds reach 115-120 kt/132-138 mph (low-end to medium TY CAT 4).

(Type 12) – **Pandanas** – Small to medium-sized trees with a palm-like trunk and multiple branches, each culminating with a crown of narrow, long, radiating leaves (fronds). Trees and leaves (fronds) are tough, but branches begin to break when winds reach about 95 kt/109 mph (high-end TY CAT 2) and leaves begin to fray longitudinally when winds reach 105 kt/121 mph (medium TY CAT 3). Trees begin to lean or blow down when winds reach 115-120 kt/132-138 mph (low-end to medium TY CAT 4).

7.3. Examples of damage to trees from tropical cyclone winds

Type 1 Trees—

The Plate 6, upper left picture shows a normal stand of coconut palms (*Cocos nucifera*) (left) and a royal palm (*Roystonia regia*) (right) with its crown broken. The coconut palms have a propensity to lean while the royal palm usually stand straight. Crowns of palm trees begin to break when winds reach about 95-100 kt/109-115 mph (high-end TY CAT 2 to low-end TY CAT 3). Palm blades can be severely torn longitudinally after 6 to 8 hours of 68-74 kt/75-85 mph sustained winds (low-end to medium TY CAT 1 winds).

The Plate 6, upper right picture shows a palm frond from a coconut palm (*Cocos nucifera*) (left). The fronds on the windward side of the crown begin to bend and point back through the crown of the palm when winds reach 65 kt/74 mph (low-end TY CAT 1). The coconut palm at the right lost its crown. This begins to occur when winds reach about 95-100 kt/109-115 mph (high-end TY CAT 2 to low-end TY CAT 3). Some green palm fronds begin ripping from the trees with sustained winds of about 65 kt/75 mph (low-end Typhoon Category 1).

The Plate 6, middle left picture shows coconut palms (*Cocos nucifera*) with twisted tops. This occurs under two types of high-shear conditions. It occurs during the eye passage of a TY CAT 3 storm, where winds reverse direction in a short period of time. It also occurs when strong TY CAT 3 winds rapidly accelerate up to low-end to medium TY CAT 4 winds, usually due to funneling caused by terrain or buildings or due to down slope accelerations.

The Plate 6, middle right picture shows an up-rooted coconut palm (*Cocos nucifera*). This occurs in near coastal areas where rising water and heavy rains combine to saturate the ground. The tree is then hit with winds of about 95-100 kt/109-115 mph (high-end TY CAT 2 to low-end TY CAT 3). At about 105 kt/120 mph (medium TY CAT 3), up to 10% of coconut palms (*Cocos nucifera*) and betelnut palms (*Areca catechu*) can be blown down when the ground is saturated. Up to 25% of these trees exposed to medium to high-end TY CAT 4 winds can be blown down and likely more than 50% of these trees exposed to medium to high-end TY CAT 5 winds can be blown down or broken off.

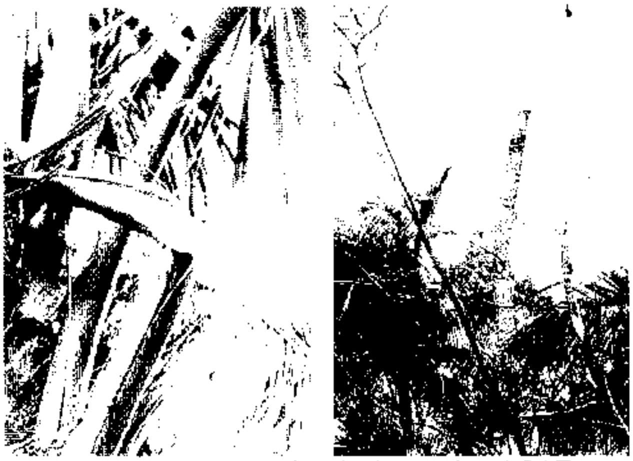
Type 2 Trees--Banana/Papaya

The Plate 6, lower left picture shows a stand of normal young banana trees (*Musa rubra*). These trees have soft, pulpy trunks that do not stand up well to even sub-hurricane-force winds.

The Plate 6, lower right picture shows damage to banana trees (*Musa rubra*) after exposure to 60-65 kt/69-75 mph (high-end TS CAT B to low-end TY CAT 1 winds).

PLATE 6


Left: Stand of coconut palm trees.
Right: Royal palm with broken crown—low-end TY CAT 3 winds


Left: Palm tree with bent frond—low-end TY CAT 1
Right: Palm tree with broken crown—low-end TY CAT 3


Palm trees with twisted crowns—medium TY CAT 3 with an eye passage or low-end to medium TY CAT 4 with unidirectional winds due to local accelerations


Coconut palm blown over—low-end to medium TY CAT 3; up to 10% can blow over in medium to high-end TY CAT 3 winds


Normal young banana trees


Banana trees—after exposure to high-end TS CAT B winds

Type 3 trees--Bamboo/Sugar cane

The Plate 7, upper left picture shows the effects of low-end to medium TY CAT 4 winds on a stand of bamboo (*Bambusa vulgaris*). Bamboo and sugar cane (*Saccharum spp.*) are fairly resilient to winds up to about 95-100 kt/109-115 mph (high-end TY CAT 2 to low-end TY CAT 3). The outer culms tend to buffer the inner culms from the strong winds, but once the winds reach medium TY CAT 2 intensity the culms begin to lean. When winds reach medium TY CAT 3 intensity, the culms begin to break.

Type 4 trees–Hedge acacia (Tangantangan)/Tamarind

The Plate 7, upper right picture shows a small tropical legume commonly referred to as hedge acacia, and known on Guam as Tangantangan and on Hawaii as Haole Koa (*Leucaena leucocephala*). The tree loses its small leaves (left image) in a fairly linear manner with increasing wind speed. Defoliation of the plant begins after a few hours of sustained winds of about 65 kt/75 mph (low-end TY CAT 1) with complete defoliation occurring after sustained winds reach about 130 kt/151 mph (high-end TY CAT 4).

Severe damage to the leaves of plants can occur from excessive deposition of sea salt spray on the foliage. This is especially damaging if the storm is "dry" with insufficient rain to flush the vegetation. The stronger the category of cyclone, the farther inland and the higher in elevation the salt deposition will occur. Coastal areas can be severely affected by salt damage in even sub-hurricane force winds, and thus, only inland, well-exposed plants should be used for wind assessment. It is likely that tamarind trees (*Tamarindus indica*) defoliate in a similar manner as the hedge acacia (tangantangan), but their response to wind has not been studied in depth.

The Plate 7, center left picture shows hedge acacia (tangantangan) trees that have been partially blown over and totally defoliated. These trees were exposed to high-end TY CAT 4 winds.

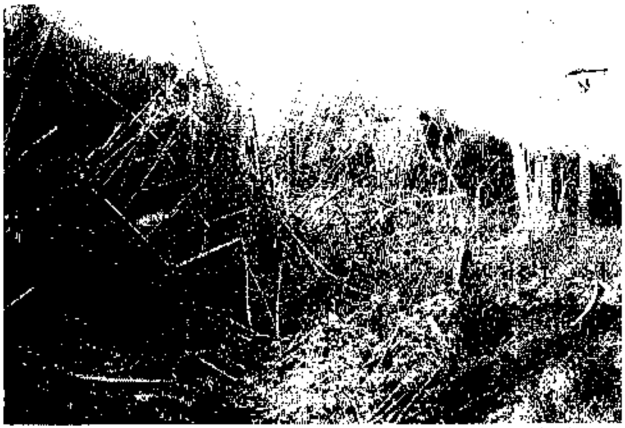
Type 5 trees--Australian pine

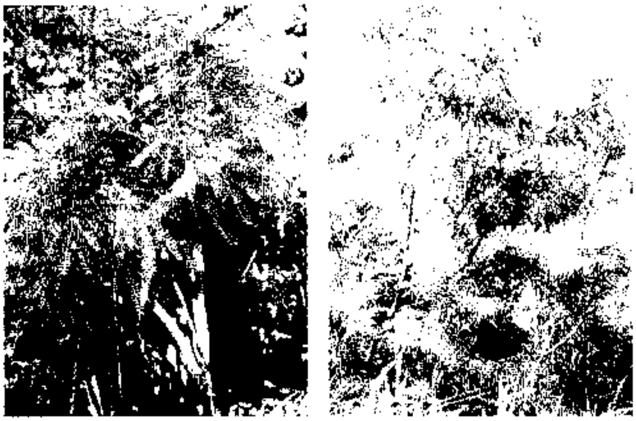
The Plate 7, center right picture shows two mature Australian pines (*Casuarina spp.*). The thick, stocky trunk and the asymmetric (pruned) branch structure (left image) are indicative of trees in areas prone to strong tropical cyclones. They are also susceptible to producing multiple trunks (right image). The trees have an extensive, yet shallow root system, making them susceptible to leaning and uprooting.

The Plate 7, lower left picture shows a broken primary branch of an Australian pine (*Casuarina spp.*). Large branches begin to break on these trees when winds reach medium to high-end TY CAT 3 intensity. Uprooting also begins at these intensities, especially if the ground is saturated or the trees are undermined by ocean inundation.

The Plate 7, lower right picture shows a totally defoliated Australian pine (*Casuarina spp.*) with severe pruning of the branches (left), and the same tree after 1 year of recovery (right). The total defoliation occurred at wind speeds of 125-130 kt/144-150 mph (high-end TY CAT 4). Major sand blasting of trunks and limbs also occurs at these wind speeds.

PLATE 7

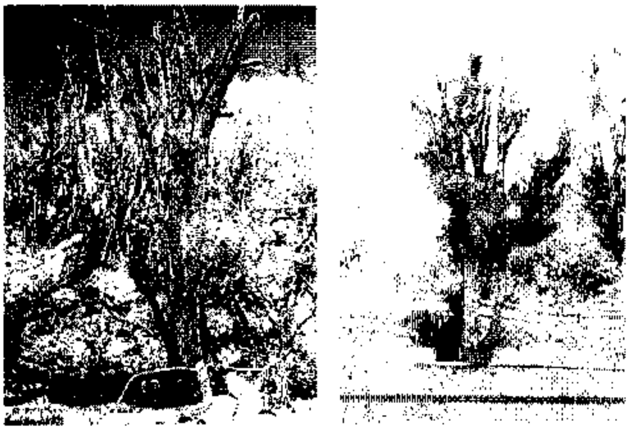

Bamboo after exposure to low-end TY CAT 4 winds.


Normal hedge acacia (tangantangan): blow-up of leaf patterns (left) and typical stand with seed pods (right).


Hedge acacia (tangantangan) after exposure to TY CAT 4 wind. Trees are mashed down and defoliated.


Australian pine with thick trunk and pruned branches (left) and with multiple trunks (right). Both are characteristic of areas prone to strong tropical cyclones.


Australian pine—with broken branch after exposure to high-end TY CAT 3 winds.


Left: Defoliated Australian pine—high-end TY CAT 4
Right: Australian pine at left after 1 year of recovery.

Type 6 trees--Banyan/Palomaria (mastwood)

The Plate 8, upper left picture (left image) shows a mature banyan tree (*Ficus prolixa*), with stabilizing "air" roots growing from the branches to the ground. The right image is a Fagot tree (*Neisosperma oppositifolia*), a common tree of the limestone forest. The irregular canopy is the result of earlier strong typhoon pruning. Both of these trees are very typhoon resistant, although they do shed limbs and many leaves on the outer-most limbs.

The Plate 8, upper right picture shows a mature polomaria (mastwood) tree (*Calophyllum inophyllum*), with a thick, stocky trunk and re-growth of pruned branches, typical of areas prone to strong typhoons (left). At right is a typical *Hibiscus tiliaceus* tree, with branches growing to the ground. Lower branches are frequently cut off to produce a more conventional looking tree. These trees grow near the coast, and when blown down, they form several trunks from the fallen trunk. They are highly typhoon and salt resistant.

Type 7 trees--Flame tree/Monkeypod/Cassia/Kapok/Eucalyptus

The Plate 8, middle left picture shows a mature poinciana (flame) tree (*Delonix regia*), with a thick, stocky trunk and re-growth of severely pruned branches, typical of these types of trees in areas prone to strong typhoons.

The Plate 8, upper right picture shows a mature poinciana (flame) tree (*Delonix regia*), with a more slender trunk and a more symmetric canopy, typical of areas less prone to strong typhoons. In areas not affected by severe tropical cyclones, the trees grow very tall with thin trunks and provide extensive canopies over rain forests.

The Plate 8, lower left picture shows a mature poinciana (flame) tree (*Delonix regia*), with a thick, stocky trunk that was heavily defoliated and uprooted. The leaves are similar to those of the tangantangan (*Leucaena spp.*), but due to significant branch breakage, it is difficult to use the defoliation as a gauge of wind speed. The leaves are also sensitive to salt spray. Uprooting can occur when winds reach 105 kt/120 mph (medium TY CAT 3 intensity) and the ground is saturated; these trees do not tend to lean much.

The Plate 8, lower right picture shows a monkeypod tree (raintree) (*Samanea saman*), with a thick, stocky trunk and large crooked branches, typical of these trees in strong typhoon-prone areas. Like the flame tree, the monkeypod sheds leaves and branches to reduce the stress on the trunk and root system.

PLATE 8

Left: Normal banyan tree with a full canopy and several stabilizing air roots.
Right: A common limestone forest tree, the Fagot tree, with a canopy that has recovered from a strong typhoon

Left: Palomeria tree with a thick trunk and pruned branches—typical of typhoon-prone areas.
Right: Typical *Hibiscus tiliaceus* tree with a thick trunk and pruned branches.

Flame tree with a thick trunk and pruned branches, typical for a strong typhoon-prone area.

Flame tree with a thinner trunk and larger branches, typical of an area prone to weaker typhoons.

Flame tree—uprooted after ground became saturated in high-end TY CAT 3 winds; note extensive, shallow root system.

Monkeypod tree with a thick trunk and pruned branches, typical of a strong typhoon-prone area.

Type 8 trees--Plumeria/Acacia/African tulip/Yoga

The Plate 9, upper left picture shows a young yellow Tacoma (*Tabebuia donnell-smithii*), with a slightly leaning trunk (left image). In the right image is a young, heavily leaning African tulip tree (*Spathodea campanulata*). This tree has likely experienced winds of at least TS CAT B intensity, but less than TY CAT 3 intensity.

The Plate 9, upper right picture shows a more mature African tulip tree (*Spathodea campanulata*), with a leaning trunk typical of areas prone to strong typhoons. A branch has split from the trunk, an occurrence that can happen when winds reach medium to high-end TY CAT 3 intensity.

The Plate 9, center left picture (left image) shows a mature plumeria tree (*Plumeria rubra*), with a stocky, slightly leaning trunk, typical of areas prone to strong typhoons. The right image is a plumeria with "multiple trunks". These trees begin to shed major branches, even near the ground, when winds reach about 105 kt/120 mph (medium TY CAT 3 intensity). They are not very prone to defoliation.

The Plate 9, center right picture shows a mature acacia tree (*Acacia confusa*), with a tall, slender leaning trunk, typical of areas prone to strong typhoons. These trees begin to shed major branches at the top when winds reach about 100 kt/115 mph (low-end TY CAT 3 intensity). They are not so prone to defoliation.

The Plate 9, lower left picture shows a severely pruned Yoga tree (*Elaeocarpus joga/sphericus*) in the early recovery stage (left image), with a tall, slender relatively straight trunk and severely pruned branches. The right image is an unidentified Type 8 tree with a trunk broken in high-end TY CAT 3 to low-end TY CAT 4 winds. Similar trees in the background show new leaf growth after 3-4 months of recovery.

The Plate 9, lower right picture shows young orchid trees (*Bauhinia spp.*), some slightly leaning, that have yet to experience the effects of even a minimal (TY CAT 1) typhoon.

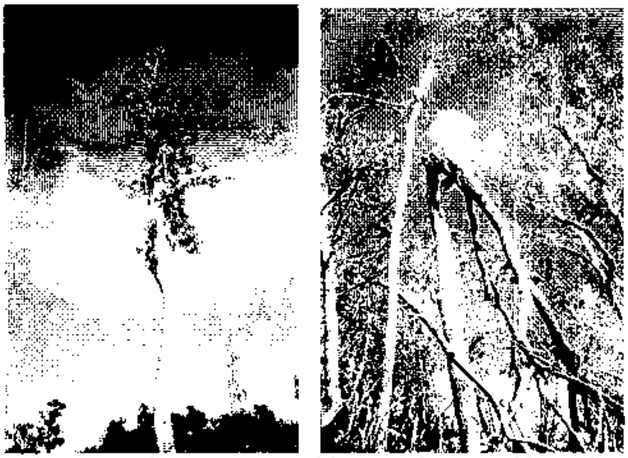
PLATE 9

Left: Young yellow Tacoma in bloom.
Right: Young African tulip tree. The leaning trunk was the result of medium to high-end TY CAT 2 winds.

African tulip tree with a split branch that occurred during high-end TY CAT 3 winds.

Mature plumeria trees with a thick trunk and pruned branches (left) and with multiple deformed trunks (right). Both are characteristic of areas prone to typhoons.

Acacia tree with leaning trunks and pruned branches, typical of limestone forests prone to strong typhoons.



Left: Recovering yoga tree with severely pruned branches and a sand-blasted trunk. Right: Unidentified tree with a trunk broken by high-end TY CAT 3 to low-end TY CAT 4 winds.

Young orchid trees, some with slightly leaning trunks.

Type 9 trees--Mango/Breadfruit

The Plate 10, upper left picture shows a mature mango tree (*Mangifera indica*) (left front) with a thick trunk, and a mature kamachile tree (*Pithecellobium dulce*) with a stocky, multiple-stemmed trunk. This trunk is typical of kamachile and some other trees of this type (see breadfruit below) in areas prone to strong typhoons.

The Plate 10, upper right picture shows a broken branch of a mango tree (*Mangifera indica*) (left image). The breakage occurred during high-end TY CAT 2 to low-end TY CAT 3 winds. This pruning helps the fragile tree avoid even more trunk breakage and uprooting than it otherwise would experience. The right image shows a mature breadfruit tree (*Artocarpus mariannensis*) with a stocky, multiple-stemmed trunk. The recovering tree has bare branches at the fringes of the canopy. These surviving bare branches are indicative of exposure to winds of at least low-end TY CAT 3 intensity.

The Plate 10, center left picture shows a mature Pacific almond tree (*Terminalia catappa*) with a stocky trunk. These trees have a propensity to lean and the crown of the tree is heavily pruned during strong typhoons. When winds reach strong TY CAT 3 intensity, the branches are pruned to a radius of about 3 feet (1 meter) around the trunk.

The Plate 10, center right picture (left image) shows a young Norfolk Island pine tree (*Araucaria excelsa*) with flexible symmetric branches. The young trees are very susceptible to uprooting in the weakest of typhoons and must be anchored. The right image is a mature Norfolk Island pine, which has lost many of its stiff, brittle branches. This pine was subjected to relatively unidirectional winds of high-end TY CAT 2 intensity. During an eye passage, the pruning will occur completely around the tree. The broken branches grow back, but are much shorter than their original length.

The Plate 10, lower left picture shows upright oleander (*Nerium oleander*) and ornamental hybiscus (background) and an oleander that has been blown over by winds of high-end TY CAT 3 intensity (foreground). Panax (*Polyscias spp.*), Bougainvillea (*Bougainvillea spp.*), and many mangroves (*Rhizophora spp.* and *Bruguiera spp.*) are blown down during strong winds. Often the roots are partially exposed, but still allow the plant to continue growing.

The Plate 10, lower right picture shows standing pandanus trees (*Pandanus tectorius*) with complete crowns (right background) and with some missing crowns (center). In the foreground is a pandanus tree (*Pandanus tectorius*) that was blown over by winds of medium to high-end TY CAT 3 intensity.

PLATE 10

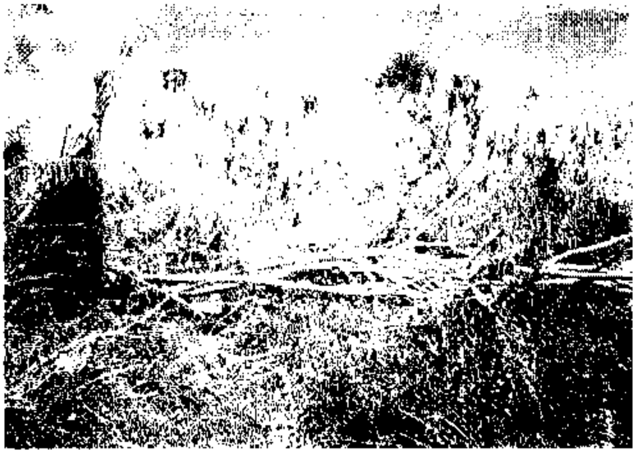

Normal mango tree (left) and normal kamachile tree (right)—with thick trunks and pruned branches, typical of areas prone to strong typhoons.


Left: A broken branch of a mango tree; damage occurred during high-end TY CAT 2 to low-end TY CAT 3 winds. Right: Recovered breadfruit tree with a thick trunk and dead branches at outer fringes indicative of damage from high-end TY CAT 3 winds.


Talisai (Pacific almond) tree with a thick trunk and pruned branches, characteristic of areas prone to strong typhoons.


Left: Young Norfolk Island pine
Right: Highly pruned Norfolk Island pine after exposure to high-end TY CAT 2 unidirectional winds.


Upright oleander and hibiscus bushes (background) and recovered oleander bushes blown over by medium TY CAT 3 winds.


Pandanas trees with complete crowns (right center), with some damaged crowns (center), and blown down by winds of medium to high-end TY CAT 3 winds.

8. APPLICATION OF THE WIND SCALE

The primary use of the scale is fairly straight-forward. When a storm is threatening a specific tropical location and warnings are issued reflecting the expected storm intensity, decision-makers can match the intensity to the appropriate cyclone Category to determine the potential wind damage and coastal wave action. In practice, disaster management officials frequently prepare a population for the destructive effects of winds one-half to one category higher than those predicted. This is to help compensate for tropical cyclone intensity prediction errors that can, at times, be large.

Assessing tropical cyclone intensity from observed damage to structures, infrastructure, and trees, and from observed coastal wave action, is more difficult. Although an accurate assessment requires considerable experience, a reasonable estimate can be made by matching the observed damage and wave action to STCS.

In applying the scale as a tool for estimating storm intensity from an actual typhoon event, one must recognize that there are many variables that can affect both the wind and its affect on trees and structures. Some of these variables include: exposure; the duration of strong winds; the age and weathering of structures; construction techniques (e. g., are metal hurricane ties and other braces used?); and for trees, the age and flexibility of the vegetation, whether or not the leaves were exposed to high levels of salt water, whether or not the salt water was flushed from the leaves by rain, and the recurrence interval between typhoon events.

For structures, perhaps the most important consideration is exposure. Structures sheltered by other structures or by vegetation, hills, etc. will receive less damage than those exposed directly to the wind. Wooden structures that are termite infested or have wood rot will be more susceptible to damage than newly built wooden structures. Thus, a newly built wooden structure may easily survive a Category 4 typhoon and 15 years later be heavily damaged by a Category 3 typhoon. Structures conforming to more stringent building codes (e.g., using hurricane ties) will be less susceptible to damage than those that don't conform to the more stringent building codes. Structures with typhoon shutters will fare better than those without shutters.

A wooden power pole may survive a Category 4 typhoon, but after years of weathering and termite infestation, it can become very susceptible to damage from a high-end Category 1 typhoon. Some poles without supporting guy-wires may be tilted or broken, while others may easily survive. If winds blow parallel to the power lines, the lines themselves act as guy-wires, stabilizing the poles. However, if winds blow perpendicular to the power lines, poles without guy-wires can become tilted or broken. Once they break, they frequently create a chain reaction, and two, three, or four adjacent poles may break or fall, dragging down power lines.

A steel-framed sheet metal structure may survive a Category 4 typhoon. However, if gaps develop in the sheet metal siding or roofing so that the wind can get under even a single metal sheet, a Category 3 typhoon can rip much of the metal from the structure and bend the supporting steel frame.

Damage to vegetation can be critically influenced by exposure as well. Plants can protect other plants where growth is dense. Sustained winds and their duration appear to have a much greater effect on damaging plants than wind gusts. While the exact relationship between vegetation damage and wind intensity and wind duration is not clear, it appears that duration is an important consideration. Salt spray can lead to severe leaf browning and defoliation of plants if they are not flushed by rain. Thus, a relatively dry storm will cause more defoliation than a wet one of comparable wind speed.

The purpose of the above discussion is to emphasize that STCS cannot be used as an exact measurement of the wind or even as a valid estimate without some understanding of the variance in observations one will encounter. Thus, when applying the scale to estimate maximum winds, one must be careful not to concentrate on the individual damage. Instead, one must assess the overall damage in order to come up with a storm wind category, then, compare the arrived at wind category with the category above and below to fine-tune and alter the final wind category determination. It may well be that the final determination is categorized as "a high-end Category 2 typhoon to a low-end Category 3 typhoon" rather than as a single, specific category. This allows one to more closely estimate the maximum winds. Despite the subjective nature of the scale, an assessment (by an experienced assessor) of the wind speed from average overall damage to structures and trees should be accurate to within 20-30 percent.

STCS considers coastal wave action according to the size of the waves hitting the fringe of the reef and entering open bays, the size of the waves inside the open bays, and the height of inundation/wave run-up from waves crossing wide reefs and narrow reefs. Table 1 shows the wave heights for the different STCS wind categories. Figure 7 illustrates the relative wave heights at different locations along a reef line and within the open bays for a typhoon of STCS TY CAT 3 intensity.

Table 1. The size of the waves hitting the fringe of the reef and entering open bays, the size of the waves inside the open bays, and the height of inundation from waves crossing wide reefs and narrow reefs.

Category	Rise (ft)	Breaking waves inside bays	Waves over 250' - 500' reefs	Inundation reefs < 250' wide
TS A	< 2	2 - 3	< 1	< 1
TS B	2 - 4	3 - 5	1 - 2	1 - 2
TY 1	4 - 6	5 - 7	2 - 3	2 - 4
TY 2	6 - 8	7 - 10	3 - 5	4 - 6
TY 3	8 - 12	10 - 15	5 - 8	6 - 10
TY 4	12 - 18	15 - 25	8 - 12	10 - 15
TY 5	18 - 30+	25 - 35+	12 - 20+	15 - 30+

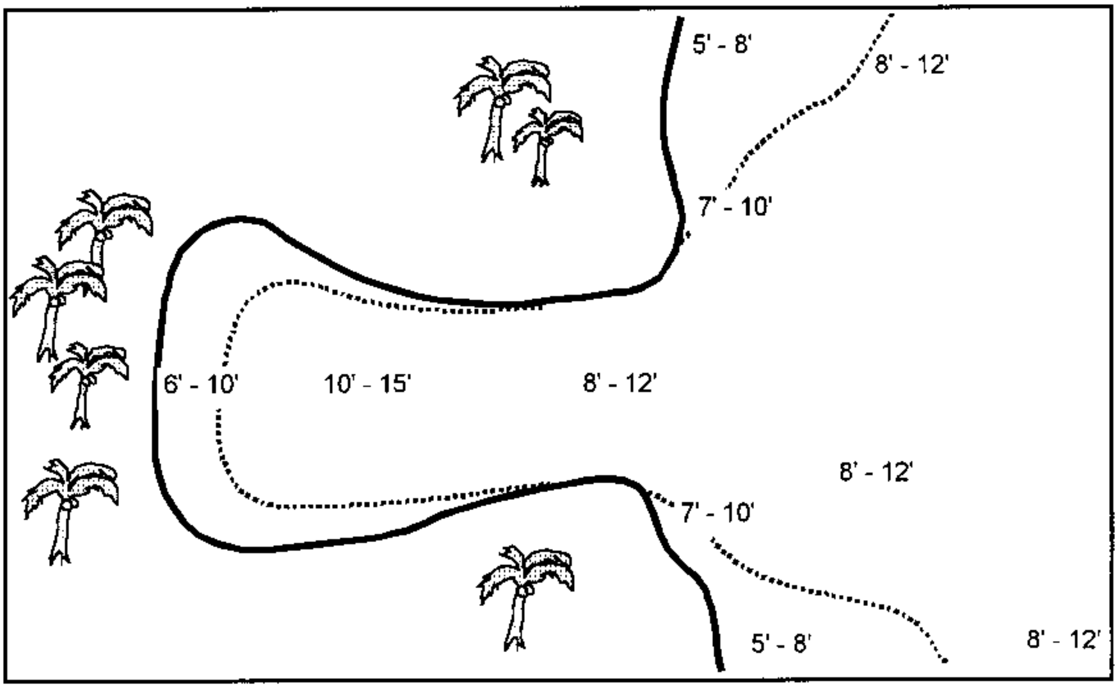


Figure 7. Coastal wave heights for waves hitting the fringe of the reef and entering open bays, the size of the waves inside the open bays, and the height of inundation from waves crossing wide reefs and narrow reefs for a TY CAT 3 typhoon.

9. DEVELOPING A WIND-DAMAGE TABLE FOR A SPECIFIC LOCATION

Appendix C is a wind-damage table or matrix that was developed for Guam using STCS. With some assistance, a similar table can be developed for any location, personalizing the scale for that specific site. Such a table is extremely valuable when rapid, accurate decisions need to be made by emergency management officials and others supporting disaster preparedness, response, and recovery efforts. It is also valuable for planners who must mitigate against future tropical cyclone damage and disruption.

10. SUMMARY

While the wind scale described herein is designed primarily for the tropical western North Pacific, it should be applicable in most other tropical areas. In light of the International Decade for Natural Disaster Reduction (INDNR), the authors invested a year of additional time to make the scale applicable to all tropical regions prone to severe winds. The World Meteorological Organization's 1993 *Global Guide to Tropical Cyclone Forecasting* (WMO 1993) indicated that such a scale did not exist but was badly needed. The publication, *Disaster Mitigation in Asia and the Pacific* (ADBM 1991), presented only one such scale (Amadore et al. 1985), but the scale was very brief in its descriptions. The authors hope that STCS will play an important role in improving the public's understanding of the potential impacts of tropical cyclones, thereby eliciting better response to warnings, and reducing unnecessary loss of life and property. As more data become available or better ways to clarify STCS for the layman become evident, the authors will evaluate the need for refinements. For example, it may be become apparent that some terms in the scale are still not fully understood and will need to be further simplified or amplified. Or, future tropical cyclones may reveal additional insight into the relationship between wind and damage, and could allow for further fine-tuning. Local modifications can also be incorporated that make STCS more appropriate to a specific basin or location. The table/matrix in Appendix C is designed to allow for such flexibility. Ideas, recommendations, and information concerning tropical cyclone damage (e.g., photos, reports, newspaper clippings, wind and inundation observations, etc.) are welcomed by the authors and may be sent to: Chip Guard or Mark Lander, Water and Environmental Research Institute, University of Guam, 303 University Drive, Mangilao, Guam, 96923 USA. They can also be faxed to (1-671) 734-8890 or e-mailed to chipguar@uog.edu.

The major wind and coastal wave parameters of STCS are summarized in Table 2.

Table 2. Saffir-Simpson Tropical Cyclone Scale (STCS) tropical storm (TS) and typhoon (TY) categories, the corresponding sustained wind and wind gust speed ranges, general description, and expected elevated water levels in bays and over reefs.

Category	Sustained Wind (mph)	Wind Gusts (mph)	Description of Damage Level	Inundation for Reefs 250'-500' wide	Inundation for Reefs <250' wide
TS A	**30-49**	**40-64**	**Weak TS**	**<1**	**<1**
TS B	**50-73**	**65-94**	**Severe TS**	**1**	**1-2**
TY 1	**74-95**	**95-120**	**Minimal TY**	**2-3**	**2-4**
TY 2	**96-110**	**121-139**	**Moderate TY**	**3-5**	**4-6**
TY 3	**111-130**	**140-167**	**Extensive TY**	**5-8**	**6-10**
TY 4	**131-155**	**168-197**	**Extreme TY**	**8-12**	**10-15**
TY 5	**156-194**	**198-246**	**Catastrophic TY**	**12-20+**	**15-30+**

DISCLAIMER

Despite the years of observation and research that led to this adaptation of the Saffiir-Simpson Hurricane Scale to the tropical Pacific region, the resulting Saffir-Simpson Tropical Cyclone Scale (STCS--pronounced STICKS) is subject to variation. The purpose of STCS is to help provide guidance to decision makers and to help trained personnel conduct post-cyclone wind assessments. To this end, STCS offers a great improvement over what is currently available. However, in nature, there are just too many variables in tropical cyclone characteristics, island and coastal morphology, structure and tree characteristics, exposures to the wind, and in the near-shore bathymetry to produce a "perfect" scale. For these reasons, the authors, the University of Guam, and any persons or organizations affiliated with the development and publication of this scale relinquish any liability that may be attributed to the scale's use.

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SIGNIFICANT CHANGES BETWEEN THE 1ST EDITION AND THE 2ND EDITION

1. The upper value of Typhoon CAT 2 was changed from 96 knots to 95 knots and the lower value of Typhoon CAT 3 was changed from 97 knots to 96 knots. This corrects mathematical conversion errors on pages 8 and 9 in the First Edition and keeps the scale consistent with the Atlantic scale. Changes were also made in appropriate tables and appendixes.

2. The upper value of Typhoon CAT 4 was changed from 136 knots to 135 knots and the lower value of Typhoon CAT 5 was changed from 135 knots to 136 knots. This corrects mathematical conversion errors on pages 10 and 11 in the First Edition and keeps the scale consistent with the Atlantic scale. Changes were also made in appropriate tables and appendixes.

3. The Coastal Inundation and Wave Action section under Tropical Storm CAT B was corrected to reflect 2-4 feet as 0.6-1.2 meters, inserting an omitted decimal point.

4. In describing the lower end (upper end) of specific typhoon wind category ranges, the terms "weak" ("strong") was changed to "low-end" ("high-end"). This was done to eliminate unnecessary confusion and to discard any idea that any typhoon-force winds are weak.

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APPENDIX A

Conversion Tables for Winds

Wind speed ranges for 10-minute average sustained winds and associated wind gusts for the various tropical storm and typhoon/hurricane wind-damage categories. Values are given in miles per hour (mph), knots (kt), kilometers per hour (km/hr), and meters per second (m/s).

Category	mph	kt	km/hr	m/s
TS A				
MSW	26-43	23-37	43-68	12-19
Gusts	40-64	35-56	65-104	18-29
TS B				
MSW	44-64	38-56	70-104	20-29
Gusts	65-94	57-81	105-150	30-42
TY 1				
MSW	65-82	57-71	105-131	30-37
Gusts	95-120	82-105	151-194	43-55
TY 2				
MSW	83-95	72-82	133-152	38-43
Gusts	121-139	106-120	196-222	56-62
TY 3				
MSW	96-113	83-98	154-181	44-51
Gusts	140-167	121-144	224-266	63-75
TY 4				
MSW	114-135	99-117	183-216	52-61
Gusts	168-197	145-170	268-315	76-88
TY 5				
MSW	136-170	118-148	218-274	61-77
Gusts	198-246	171-216	317-400	89-112

APPENDIX B

Common names, local Chamorro names (*italicized* (left side)), scientific names [genus and species (*italicized*), family (capitalized)], and type classifications for selected tropical trees.

Common/*Chomorro* Names	Type	Genus/Species Names	Family Name
Acacia/Ear-pod wattle/Formosan koa/ *Sosugi*	(8)	*Acacia confusa/auriculiformis*	FABACEAE (LEGUMINOSAE)
African tulip tree	(8)	*Spathodea campanulata*	BIGNONIACEAE
Australian pine/Casuarina /Ironwood Beach sheoak/*Gago*	(5)	*Casuarina equisetifolia/littorea*	CASUARINACEAE
Avacado/*Alageta*	(9)	*Persea americana*	LAURACEAE
Bamboo/*Pi'ao/Palaoan*	(3)	*Schizostachyum/Bambusa vulgaris*	POACEAE (GRAMINAE)
Banana/*Aga*	(2)	*Musa rubra*	MUSACEAE
Banyan/Strangler Fig/*Nunu*	(6)	*Ficus benghalensis/prolixa/obliqua*	MORACEAE
Baobab/Monkey-bread tree/Dead-rat tree	(6)	*Adansonia digitata*	BOMBACACEAE
Betelnut palm/*Pugua'*	(1)	*Areca catechu*	ARECACEAE (PALMAE)
Blue marble tree /*Yoga*	(8)	*Elaeocarpus joga*	TILIACEAE (ELAEOCARPACEAE)
Bougainvillea/*puti tai nubio*	(12)	*Bougainvillaea spp.*	NYCTAGINACEAE
Breadfruit/*Lemai*	(9)	*Artocarpus incisus*	MORACEAE
Cassia/Shower trees	(7)	*Senna (Cassia) alata/fistula/glauca/grandis/ javanica/siamea*	FABACEAE (LEGUMINOSAE)
Chi'ute	(8)	*Cerbera dilatata*	APOCYNACEAE
Coconut palm/*Niyog*	(1)	*Cocos nucifera*	ARECACEAE (PALMAE)
Coral tree/Catclaw tree/*Gaogao*	(9)	*Erythrina variegata*	FABACEAE (LEGUMINOSAE)
Crepe Myrtle/Rose of India	(8)	*Lagerstroemia speciosa*	LYTHRACEAE
Cucumber tree/Pickle tree	(9)	*Averrhoa bilimbi*	OXALIDACEAE
Eucalyptus/Gum tree	(7)	*Eucalyptus camaldulensis/citriodora/ deglupta/saligna/tereticornis*	MYRTACEAE
Fagot/Fago	(6)	*Neisosperma oppositifolia*	APOCYNACEAE
Faia	(6)	*Tristiropsis obtusangula*	SAPINDACEAE
Faniok	(7)	*Merrilliodendron megacarpum*	ICACINACEAE
Fig/Dyer's Fig/*Hodda*	(6)	*Ficus tinctoria*	MORACEAE
Guava/*Abas*	(9)	*Psidium guajava*	MYRTACEAE
Hedge acacia/Haole Koa/*Tangantangan*	(4)	*Leucaena leucocephala/glauca*	FABACEAE (LEGUMINOSAE)
Common/Local Names	Type	Genus/Species Names	Family Name
Hibiscus/Sea-Hibiscus/Corkwood/*Pago*	(6)	*Hibiscus tiliaceus*	MALVACEAE
Ifil//Ipil tree/*Ifit*	(8)	*Intsia bijuga*	FABACEAE (LEGUMINOSAE)
Jackfruit/Jakfruit/*Langka*	(9)	*Artocarpus heterophyllus*	MORACEAE
Kapok/Silk Cotton tree/*Algidon*	(7)	*Ceiba pentandra*	BOMBACEAE

Mangrove/Many-Petaled Mangrove/ *Manglen Lahi*	**(11)**	***Rhizophora apiculata/samoensis/mucrorata* *Bruguiera gymnorhiza***	**RHIZOPHORACEAE**
Mango/*Mangga*	**(9)**	***Mangifera indica***	**ANACARDIACEAE**
Monkeypod/Raintree/*Trongkon-mames*	**(6)**	***Samanea saman***	**FABACEAE (LEGUMINOSAE)**
Norfolk Island pine	**(10)**	***Araucaria excelsa***	**ARAUCARIACEAE**
Madras Thorn/Camachile/*Kamachile*	**(9)**	***Pithecellobium dulce***	**FABACEAE (LEGUMINOSAE)**
Oleander	**(11)**	***Nerium oleander***	**DOGBANE**
Orchid tree	**(8)**	***Bauhinia spp.***	**FABACEAE (LEGUMINOSAE)**
Pacific almond/*Talisai*/*Talisei*	**(8)**	***Terminalia catappa***	**COMBRETACEAE**
Palomaria/Mastwood/*Da'ok*/*Da'og*	**(6)**	***Calophyllum inophyllum***	**CLUSIACEAE**
Panax/Ming aralia/*Pepega*	**(11)**	***Polyscias fruiticosa/grandifolia***	**ARALIACEAE**
Pandanus/Screw pine/*Pahong*/*Kafu*/*Fatsao*	**(12)**	***Pandanus dubius/tectorius/conoideus***	**PANDANACEAE**
Papaya/*Pawpaw*	**(2)**	***Carica papaya***	**CARICACEAE**
Paper Bark tree	**(7)**	***Melaleuca leucadendra/linariifolia/hypericifolia***	**MYRTACEAE**
Pisonia/Lettuce tree/*Umumu*	**(9)**	***Pisonia grandis/umbellifera***	**NYCTAGINACEAE**
Plumeria/*Kalachucha*	**(8)**	***Plumeria rubra/obtusa***	**APOCYNACEAE**
Poinciana/Flame tree /*Arbol de Fuego*	**(7)**	***Delonix regia***	**FABACEAE (LEGUMINOSAE)**
Rosewood/*banalo pule*	**(6)**	***Thespesia populnea***	**MALVACEAE**
Royal palm	**(1)**	***Roystonea regia***	**ARECACEAE (PALMAE)**
Siris tree/East Indian walnut	**(8)**	***Albizia lebbeck***	**FABACEAE (LEGUMINOSAE)**
Soursop/*Laguanaha*	**(9)**	***Annona muricata***	**ANNONACEAE**
Star apple	**(9)**	***Chrysophyllum cainito***	**SAPOTACEAE**
Star fruit/*bilimbinis*	**(9)**	***Averrhoa carambola***	**OXALIDACEAE**
Sugar cane/*Tupo*	**(3)**	***Saccharum edule/officinarum***	**POACEAE (GRAMINAE)**
Tacoma (pink and yellow varieties)	**(8)**	***Tabebuia donnell-smithii***	**BIGNONIACEAE**
Tamarind/*Kalamendo'*	**(4)**	***Tamarindus indica***	**FABACEAE (LEGUMINOSAE)**
Yokewood	**(8)**	***Catalpa longissima***	**BIGNONIACEAE**

APPENDIX C

A TROPICAL CYCLONE WINDSPEED--DESTRUCTION SCALE FOR THE TROPICAL PACIFIC

TROPICAL CYCLONE CATEGORY	**DEBRIS SIZE (in air)**	**RESIDENTIAL BUILDINGS**		**GOVERNMENT COMMERCIAL BUILDINGS**		**INFRASTRUCTURE** **POWER/PHONE/CABLE TV**			**PORTS OF ENTRY**		**VEGETATION/ AGRICULTURE**	**INUNDATION ABOVE HIGH TIDE**	
TROPICAL STORM CATEGORIES		**Wood**	**Concrete**	**Sheet Metal**	**Concrete**	**Wood Poles**	**Concrete Poles**	**Trans Lines**	**Sea Port**	**Air Port**	**Exposed Vegetation**	**Inside Bays Reefs <250'**	**Over Reefs 250'-500'**
TS CAT A Sus: 30-49 mph Gust:40-64 mph ***WEAK***	Small leaves and twigs	Thatch damaged	N	N	N	N	N	N	N	Light, unsecured aircraft moved	Salt spray; some serious crop damage	<1'	<1'
TS CAT B Sus; 50-73 mph Gust: 65-94 mph ***SEVERE***	Some sheet iron & plywood becomes airborne	Thatch destroyed; poorly attached sheet iron, plywood	N	Gaps in sheet metal begin to open	N	A few un-guyed poles tilt; very rotten may snap	N	A few secondary lines downed	N	Light unsecured aircraft may flip; debris blown on runways	Heavy salt spray; moderate damage to banana trees; severe damage to crops	1-2'	1-2'

A TROPICAL CYCLONE WINDSPEED--DESTRUCTION SCALE FOR THE TROPICAL PACIFIC

TROPICAL CYCLONE CATEGORY	**DEBRIS SIZE (in air)**	**RESIDENTIAL BUILDINGS**		**GOVERNMENT COMMERCIAL BUILDINGS**		**INFRASTRUCTURE**					**VEGETATION/ AGRICULTURE**	**INUNDATION ABOVE HIGH TIDE**	
						POWER/PHONE/CABLE TV			**PORTS OF ENTRY**				
TYPHOON CATEGORY		**Wood**	**Concrete**	**Sheet Metal**	**Concrete**	**Wood Poles**	**Concrete Poles**	**Trans Lines**	**Sea Port**	**Air Port**	**Exposed Vegetation**	**Inside Bays Reefs <250’**	**Over Reefs 250’-500’**
TY CAT 1 Sus: 74-95 mph Gust: 95-120 mph ***MINIMAL***	Many pieces of sheet iron, plywood, palm fronds airborne	Some damage to termite-weakened roofs	Some unprotect windows broken by debris	Gaps in sheet metal made larger & roofing starts to roll	N	Termite-weakened poles begin to snap	Un-guyed hollow begin to tilt	A few 2ndary lines downed	Some small craft torn from moorings; some pier damage	Considerable debris blown onto runways; unhangered light aircraft damaged	Palm fronds begin to crimp through crown; major damage to bananas & crops; <10% defoliation of plants	2-4’	2-3’
TY CAT 2 Sus: 96-110 mph Gust: 121-139 mph ***MODERATE***	Much sheet iron, limbs plywood, palm fronds, 2X4s airborne	Much damage to termite-weakened roofs, doors, windows	Many unprotect windows broken by debris	Large openings in sheet iron with gaps; edges of well-built roofs leak	Some unprotect windows cracked by debris; some roof tiles damaged	Several termite-weakened poles snap	Several unguyed hollow poles tilt	Many secondary lines downed	Many small craft torn from moorings; considerable pier damage;	Unhangered light aircraft destroyed; heavy aircraft hit by debris; terminal windows cracked	Palm fronds ripped from palm trees; some green coconuts blown from palms; some branches/ limbs snapped; many breadfruit, mangos, etc blown from trees; 10-20% defoliation	4-6’	3-5’
TY CAT 3 Sus: 111-130 mph Gust: 140-167 mph ***STRONG***	Many light and some medium-sized objects become airborne;e.g plywood, sheet iron, 2X4s	Weakly constructd & termite-weakened housed heavily damaged or destroyed	Numerous unprotectd windows broken by debris; exposed A/C damaged	Buildings with gaps in sheet iron heavily damaged or destroyed; edges of well-built roofs leak	Some unprotect windows broken by debris; some roof tiles become airborne	Many snapped/downed; most termite-weakened destroyed	Some unguyed hollow poles snapped/downed	Some primary & most 2ndary lines downed	Some large ships torn from moorings & driven onto reefs; many small craft sunk; empty containers blown	Heavy aircraft damaged by debris; empty containers can become airborne; some terminal windows broken; nav aids damaged	Many green coconuts blown from palms; up to 50% palm fronds bent or torn off; crown of palms begin to blow off; many small limbs snapped; most breadfruit, mangos, etc blown from trees: 20-50% defoliation	6-10’	5-8’

A TROPICAL CYCLONE WINDSPEED--DESTRUCTION SCALE FOR THE TROPICAL PACIFIC

TROPICAL CYCLONE CATEGORY	DEBRIS SIZE (in air)	RESIDENTIAL BUILDINGS		GOVERNMENT COMMERCIAL BUILDINGS		INFRASTRUCTURE					VEGETATION/ AGRICULTURE	INUNDATION ABOVE HIGH TIDE	
						POWER/PHONE/CABLE TV			PORTS OF ENTRY				
TYPHOON CATEGORY		**Wood**	**Concrete**	**Metal**	**Concrete**	**Wood Poles**	**Concrete Poles**	**Trans Lines**	**Sea Port**	**Air Port**	**Exposed Vegetation**	**Inside Bays Reefs <250”**	**Over Reefs 250’-500’**
TY CAT 4 Sus:131-155 mph Gust:168-197 mph *VERY STRONG*	Many medium-sized objects become airborne; e.g., washers, roof tiles, glass	Even well-built structures heavily damaged or destroyed	Numerous windows implode; good shutters survive; doors fail	Most, even well-built structures heavily damaged or destroyed	Most unprotect windows broken by debris; many roof tiles become airborne	Most wood poles downed/ snapped;	Many unguyed and some guyed hollow poles snapped/downed	Many primary & all 2ndary lines downed	Many large ships torn from moorings & driven onto reefs; empty containers become airborne; cranes heavily damaged	Large aircraft damaged by debris; full containers airborne; many tower & terminal glass broken; hanger doors & nav aids destroyed	Most green coconuts blown from palms; up to 75% palm fronds bent or torn off, many palm crowns blown off, many large limbs snapped; most breadfruit, mangos, etc blown from trees; 50-80% defoliation	10-15’	8-12’
TY CAT 5 Sus:156-194 mph Gust:198-246 mph ***DEVASTATING***	Large objects become airborne; e.g., cars, washers	All wooden buildings destroyed	Shutters, windows, doors, A/C fail	All metal buildings destroyed	Some structural damage from large debris; shutters, A/C. destroyed	All wood poles destroyed	Some steel & solid concrete & numerous hollow poles downed	Most primary lines downed	All large ships torn from moorings & driven onto reefs or sunk; full containers become airborne; cranes destroyed	Large aircraft heavily damaged; all terminal windows & doors fail; hangered large aircraft may be damaged	All green coconuts blown from palms; up to 100% palm fronds bent or torn off, numerous palm crowns blown off. many large limbs snapped; most breadfruit, mangos, etc blown from trees; up to 100% defoliation	15-30’+	12-20’+

Abbreviations

WP	wooden electrical power pole
CP	concrete electrical power pole
Line	electrical power lines
AP	international (commercial) airport
PRT	commercial seaport
2ndary	refers to secondary electrical power lines, phone lines, and cable TV lines

APPENDIX D

Tropical Cyclone Damage Category and Minimum Pressure Relationships

Minimum sea-level pressure associated with the various tropical cyclone categories for various tropical cyclone basins.

TC Wind Category	1-min Sustained Wind (mph)	1-min Sustained Wind (kt)	Minimum[1] Sea-Level Pressure Northwest Pacific (millibars/inches)	Minimum[2] Sea-Level Pressure Atlantic (millibars/inches)	Minimum[3] Sea-Level Pressure Northern Australia (millibars/inches)
TS CAT A	30 - 49	26 - 43	1004 – 991 / 29.65 - 29.26	1010 - 1000 / 29.82 - 29.53	1000 - 993 / 29.53 - 29.32
TS CAT B	50 - 73	44 - 63	990 - 977 / 29.23 - 28.85	999 - 990 / 29.50 - 29.23	992 - 979 / 29.29 - 28.91
TY CAT 1	74 - 95	64 - 82	976 - 956 / 28.82 - 28.23	989 - 980 / 29.20 - 28.94	978 - 969 / 28.88 - 28.61
TY CAT 2	96 - 110	83 - 95	955 - 947 / 28.20 - 27.96	979 - 965 / 28.91 - 28.50	968 - 961 / 28.58- 28.38
TY CAT 3	111 - 130	96 - 113	946 - 927 / 27.93 - 27.37	964 - 945 / 28.47 - 27.90	960 - 949 / 28.35 - 28.02
TY CAT 4	131 - 155	114 - 135	926 - 905 / 27.34 - 26.72	944 - 920 / 27.88 - 27.16	948 - 934 / 27.99 - 27.58
TY CAT 5	156 - 194	136 - 170	904 - 870 / 26.69 - 25.69	919 - 890 / 27.14 - 26.28	933 - 905 / 27.55 - 26.72

[1] From Atkinson and Holliday (1977); also used in the Southwest Pacific and the Indian Ocean
[2] From Kraft (1961)
[3] From Love and Murphy (1985)

ACRONYMS

ADBM	**Asian Development Bank, Manila (Philippines)**
AOML	**Atlantic Oceanographic and Meteorological Laboratory (Miami, FL)**
BOM	**(Australian) Bureau of Meteorology (Melbourne, Australia)**
CAT	**Category (referring to tropical cyclone wind category)**
HRD	**Hurricane Research Division (at AOML, Miami, FL)**
INDNR	**International Decade for Natural Disaster Reduction**
IWTC-IV	**Fourth International Workshop on Tropical Cyclones (held in Haikow, Hainan Province, China, 21-30 April 1988 under World Meteorological Organization sponsorship)**
JTWC	**Joint Typhoon Warning Center, Pearl Harbor, Hawaii (located at Nimitz Hill, Guam from May 1959 until January 1999)**
NHC	**National Hurricane Center (now the Tropical Prediction Center/National Hurricane Center), Miami, Florida**
NOAA	**National Oceanic and Atmospheric Administration**
OFCM	**Office of the Federal Coordinator for Meteorological Services and Supporting Research**
ONR	**Office of Naval Research**
SSHS	**Saffir-Simpson Hurricane Scale**
STCS	**Saffir-Simpson Tropical Cyclone Scale (pronounced STiCkS)**
TS	**Tropical Storm**
TY	**Typhoon**
UOG	**University of Guam**
WERI	**Water and Environmental Research Institute**
WMO	**World Meteorological Organization**