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THESIS

A PROBABILISTIC APPROACH TO TROPICAL CYCLONE CONDITIONS OF READINESS (TCCOR)

by

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13. ABSTRACT (maximum 200 words)

Tropical Cyclone Conditions of Readiness (TCCOR) are set at DoD installations in the Western Pacific to convey the risk associated with the onset of destructive winds from approaching tropical cyclones. In this thesis, the methods by which TCCOR are set were analyzed to determine if objective and/or probabilistic guidance could improve the process. The Tropical Prediction Utility (TPU) was developed by forecasters at Yokosuka, JA and the Joint Typhoon Warning Center as a means of standardizing TCCOR forecasts using elements from JTWC official warnings. The TPU was used to recreate TCCOR timelines for 42 different cases affecting military bases at Guam, Kadena, JA, Sasebo, JA, and Yokosuka, JA during the 2002 – 2007 typhoon seasons. These timelines were then compared to historical TCCOR timelines and wind observations to identify any trends and biases in set time and duration for each TCCOR. A wind speed probability model was also used to compare the timelines to the wind observations and to categorize them based on consistent trends in probability at each predicted and historical TCCOR. The results suggest that potential biases exist in the Tropical Prediction Utility that tend to predict TCCOR earlier than they were set in practice. Although clear trends were identified between wind speed probabilities and elevated TCCOR, statistical uncertainties exist when using the probabilities to discern between "hits" and "false alarms." While this thesis identified basic traits in TCCOR settings, a larger sample of cases is needed for further study to determine factors that discriminate between hits and false alarms.

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A PROBABILISTIC APPROACH TO TROPICAL CYCLONE CONDITIONS OF READINESS (TCCOR)

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I.   INTRODUCTION

A.   MOTIVATION AND OBJECTIVE

Roughly one third of the world's annual tropical cyclones form in the Western North Pacific Ocean (WESTPAC). With an average of 31 tropical cyclones every year, this ocean basin is by far the most active tropical cyclone region on earth (JTWC 2007). Though the official WESTPAC typhoon season starts 1 June and lasts until the end of November, storms can occur in every month of the year with peak activity in August and September (Figure 1). In addition to the large frequency of storms, this area of the world also experiences the largest and most intense tropical cyclones. Over half of the tropical cyclones that occur here every year will further develop into typhoons (maximum sustained surface winds of at least 64 knots) and roughly four to five of those will attain the status of "super typhoons" with maximum sustained winds of at least 130 knots. With a significant amount of U.S. and allied military presence throughout the WESTPAC, the challenge of accurately forecasting the formation and movement of each of these storms is not only a matter of safety but also one of national security.
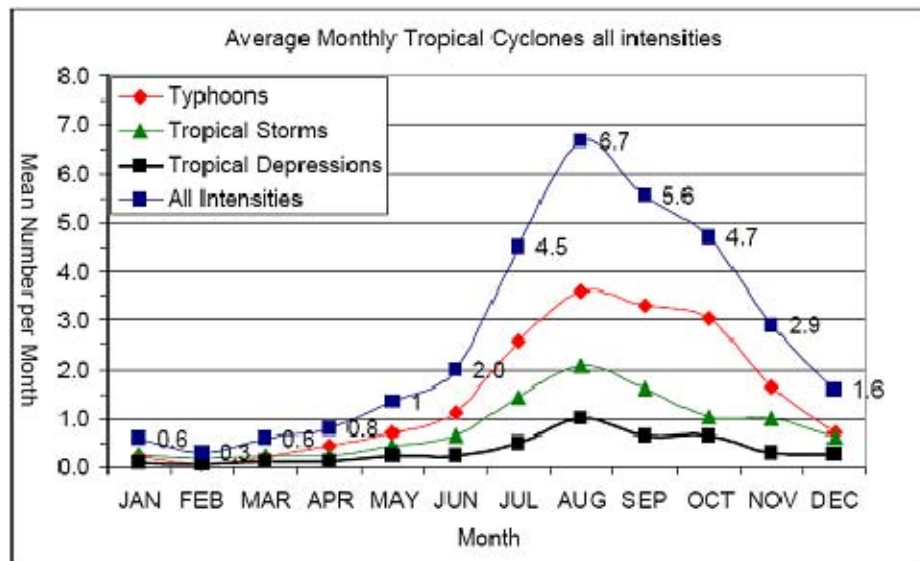
Figure 1.   Average monthly tropical cyclone frequency for the Western North Pacific, 1959 - 2007 (from http://metocph.nmci.navy.mil/jtwc/atcr/2007atcr/2007atcr.pdf)

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Having maintained a substantial presence in the WESTPAC since World War II, the U.S. military is all too familiar with the threat posed by the frequent typhoon activity within the region. Within a ten month period from December 1944 to October 1945, no fewer than three typhoons struck the U.S. Pacific Fleet. Perhaps the most infamous of these incidents occurred on December 18, 1944 when the ships of ADM Halsey's Task Force 38 were caught directly in the path of a typhoon east of the Philippines. Three ships were sunk, over 146 aircraft were destroyed or seriously damaged (Figure 2), and 790 lives were lost (U.S. Navy Historical Center). Six months later, seven more ships, 76 aircraft and 6 men were lost as a storm struck the fleet near Okinawa. Finally, in October of 1945, heavy seas from yet another typhoon sank a dozen more ships and forced many more ashore near Buckner Bay, Okinawa in addition to ravaging the shore installations. As a result of the heavy losses inflicted by nature's fury, the Navy established its own weather forecast stations throughout the Pacific to stay apprised of any potentially hazardous weather that may threaten fleet assets year round.

Figure 2. The bow of the USS Hornet (CV-12) was one of several carriers damaged after weathering a WESTPAC typhoon on June 4–5, 1945. (from http://www.navsource.org/archives/02/12.htm#021252)

Today, the Joint Typhoon Warning Center (JTWC) is a Department of Defense agency located in the heart of the Pacific at Naval Base Pearl Harbor, Hawaii. It is

charged with the responsibility of issuing tropical cyclone warnings for the Pacific and Indian Oceans, 24 hours a day, 365 days a year. These warnings are promulgated to the applicable DoD assets throughout the theater where local operational commanders use them to determine when and how to prepare their bases for the impacts of each storm. When it is deemed necessary, the base authorities warn their personnel of the approaching threat by issuing Tropical Cyclone Conditions of Readiness (TCCOR), as defined in Table 1.

Table 1.   TCCOR Definitions(from Okinawa area joint Standard Operating Procedure
for Natural Disasters)

TCCOR IV: Trend indicates a possible threat of destructive winds of the force indicated within 72 hours. *Stock up on food and emergency supplies.*

TCCOR III: Destructive winds of the force indicated are possible within 48 hours. *Initiate General clean up around home and offices.*

TCCOR II: Destructive winds of the force indicated are anticipated within 24 hours. *Remove or secure all outside items.*

TCCOR I: Destructive winds of the force indicated are anticipated within 12 hours. *No school for DoDDS students. Staff and teachers will work normal hours, unless changed by DoDDS superintendent. Fill any containers you can use for water storage. If you live in low lying quarters, make arrangements to stay with a friend. Make final check of food and other supplies.*

TCCOR I Caution: Sustained winds of 34 to 49 kt (39-56 MPH) with frequent gusts of 50 to 59 kt (58 to 68 MPH) are occurring at a particular installation. *All nonessential personnel will be released to their quarters at this time. Staff and teachers return home or remain home. Base Exchange, shops, Commissary, shoppettes, gas station, service facilities, clubs, restaurants, rec. facilities and Post Office will close. Movement about the base should be kept to a minimum. Base security will enforce "essential vehicles only" policy.*

TCCOR I Emergency: Sustained winds of 50 kt (58 MPH) and up or frequent gusts 60 kt (69 MPH) or greater are occurring at a particular installation. *All outside activity is prohibited.*

TCCOR I Recovery: When sustained winds fall below 50 kt and gusts of 60 kt or greater are no longer occurring. *Nonessential functions remain closed unless directed by the commander. All but emergency essential personnel remain in their quarters.*

Storm Watch: The weather system is expected to pass dangerously close to the installation and any shift in track or increase in intensity may result in rapid elevations in TCCORs and destructive force winds occurring on short notice. At minimum, sustained damaging force winds of 34 to 49 kt with significant higher gusts of up to 59 kt may be experienced when this condition is set. *All military and civilian personnel will return to work within 2 hours or at normal duty hours unless otherwise instructed by their commander. The Commissary and Exchange will resume operation unless otherwise directed by the installation commander.*

All Clear: The meteorological system has passed and the threat is over and it is safe to go outdoors. *All hazards have been cleared. DoDDS teachers, staff and students will return to school during normal working hours.*

Commanders, Officers-in-charge, and Commanding Officers are not limited from taking any prudent action to protect life or property by the provisions of USFJINST 15-4001, COMNAVFORJAPANINST 3140.4, CFASINST 5000.1G, CFASINST 3440.1A, and the guidance provided below (not all inclusive) from CFASINST 3006.1:

With the setting of any TCCOR, normal operations on the base are interrupted and military and civilian personnel alike are set into motion completing a well rehearsed

series of preventative measures (in italics in Table 1) which require many man hours of work to accomplish. Major assets such as ships, submarines and aircraft must each be secured either in port, or in hangars, or sortied to sea or to another base often thousands of miles away. As the storm approaches, higher TCCOR levels are set requiring more and more preparations from virtually the entire base work force. This inevitably interferes with the day to day military routine, training, exercises and even operations critical to national security. During the course of a typical tropical cyclone season, it is not uncommon for numerous bases in the WESTPAC to be threatened and/or struck by multiple powerful storms. The costs of adequately preparing the base and its personnel in each case can total millions of dollars every year.

Since its inception in 1959, the JTWC has continuously developed and updated its forecast methodology and expanded its computational resources to better achieve the mission of protecting DoD assets in the Pacific. With an obvious correlation between the accuracy of their forecasts and the resulting operational and economic impacts at every installation throughout the region, a great deal of emphasis is placed on ensuring the safety of personnel and military assets through the timely issuance of TCCOR while at the same time avoiding unnecessary and costly preparations and interruptions to operational readiness due to "false alarms". In recent years, JTWC has been given responsibility for recommending TCCOR for some military installations in WESTPAC, including Yokosuka and Sasebo, Japan. During this time, a deterministic approach to setting TCCOR was derived largely through simple calculations involving the storm speed of advance (SOA), the distance from the threatened military installation, and the extent of the destructive wind swath surrounding the storm. The focus of this thesis is to examine current TCCOR forecasting methods and to determine if objective guidance and probabilistic methods can be used to improve the process and better convey the risk of potential damage at fleet concentration areas. The end goal would be to potentially save costs in terms of time, money and operational readiness.

B. MILITARY INSTALLATIONS AND TYPHOON PROCEDURES

The JTWC is responsible for issuing Tropical Cyclone Warnings in the Pacific from East Africa to 120 degrees West longitude. Official guidance states that a tropical cyclone threat exists when a forecast tropical cyclone track is located or expected to pass within 180 NM of any DoD installation or when the setting of TCCOR IV is anticipated within 24 hours anywhere within this Area of Responsibility (AOR) (CDO SOP 010). When this situation occurs, a great deal of coordination between JTWC and the TCCOR authority for the threatened installation takes place and is maintained on a near hourly basis. Every military installation under JTWC's purview maintains a hazardous weather plan unique to its particular location, geography, and type of assets on station. These plans require many personnel and usually days of advance notice in advance as possible to carry out effectively. For the purposes of this research four very different and unique installations, scattered throughout the Western North Pacific as shown in Figure 3, were selected based on their strategic importance to the military and the frequent number of annual tropical cyclone incidents.

1. Guam

As the westernmost U.S. territory, Guam is located almost 4,000 miles west of Hawaii, and is the largest and most heavily populated island in Micronesia. Guam is strategically very important to the U.S. military due largely to its far western position in the Pacific and also due to the unique support and repair facilities located there. Of the nearly 175,000 residents of the island, roughly 10,000 are military members and their families. This number will inevitably grow as the DoD completes an estimated $10.3 billion defense build up on Guam over the next several years (Kan, 2006). Guam is currently home to the Commander, Submarine Squadron Fifteen, the Navy's only forward deployed nuclear submarine squadron, the submarine tender USS FRANK CABLE, four Military Sealift Command ships, and is frequently host to a variety of other units from all over the Pacific. Guam shipyard and the Ship Repair Facilities include a multi-million dollar dry dock and many other assets and capabilities not found elsewhere in the Western Pacific.

The island's location also holds equal strategic significance for the U.S. Air Force as it has been the focal point of American air power (Figure 3) in the Western Pacific since World War II. Andersen Air Force Base, located on the north end of the island, is home to units of the 13th Air Force and numerous supporting tenant commands. The base serves as one of only four U.S. Bomber Forward Operating Locations in the world, providing support to units deploying to Europe, Southwest Asia, and elsewhere in the Pacific. The virtually unrestricted air space surrounding Guam and the Naval bombing range located just 150 NM to the North at Farallon de Madinilla Island creates an ideal year round training environment that hosts several major joint exercises involving hundreds of ships and aircraft and thousands of personnel annually. The island is also home to the only conventional air launched cruise missiles (CALCM) located outside of the United States.

Figure 3. Four F-15 Eagles and two B-2 Spirit Bombers are packed into a protective hangar as TCCOR I is set at Anderson Air Force Base, Guam on August 6, 2006 (from http://www.af.mil/photos/media_search.asp?q=typhoon&page=5).

Coincidentally, the geographic location that affords Guam its strategic importance also places it directly in the region of the WESTPAC where most tropical cyclones form. The small size of the island places 100% of the total population at risk from destructive winds associated with a tropical storm. Though most storms do not hit the island directly and often pass by before reaching peak strength, the island has been severely impacted by many powerful typhoons over the years. Between 1992 and 2002, six typhoons passed directly over the island. In November of 1962, Supertyphoon Karen struck Guam with

sustained winds of 155 mph, killing 11 people, destroying most of the housing on the island, and costing an estimated $250 million in total damages (over US$1.6 billion in 2008 terms) (World Bank). More recently, Supertyphoon Pongsona pounded Guam with over 150 mph winds for nearly twelve hours in early December 2002. The storm caused extensive damage to both Air Force and Navy assets, destroying several hangars and harbor facilities and requiring numerous U.S. Navy ships and submarines to sortie out to sea until the harbor could be made safe for navigation several days later.

Due to the constant risk of tropical cyclones developing nearby and impacting Guam within 72 hours at any time of the year, the island remains in TCCOR 4 year round. As a storm approaches, the Office of Civil Defense (OCD) receives forecasts from the National Weather Service (NWS) and the JTWC. The OCD then coordinates with the Governor to determine how and when to notify the public and which actions to take to prepare for the storm. TCCOR for the civilian populace are set at the authority of the Governor in close coordination with the U.S. Naval Forces Marianas on the island (Guam Emergency Response Plan). The Commander, Naval Forces Marianas sets TCCOR for all DoD installations on Guam which, depending on the situation, can differ from those set by the Governor for the rest of the island.

2. Kadena, Japan

Located approximately 1200 miles to the Northwest of Guam in Japan's Southernmost prefecture of Okinawa lies another strategically significant foothold of U.S. military power in the WESTPAC. Kadena Air Base, along with numerous other DoD installations on Okinawa, is only a one hour flight away from the Taiwan Strait, mainland China, and the Korean peninsula. The island's close proximity to these politically sensitive regions and its large size (approx. 485 square miles) make it an ideal location for a multitude of DoD assets and a key base of operations for a number of crisis response scenarios. As one of the largest U.S. air bases in the world, Kadena hosts a wide variety of Navy, Air Force and Marine Corps aircraft and nearly 10,000 personnel. The nearby harbor facilities are key to many of the Navy and Marine Corps operations in the WESTPAC and are frequently visited by the large number of Navy ships and submarines operating in the Pacific.

Like Guam, the military installations on Okinawa have a long and tattered history of typhoon related incidents. Within a 37 day period in August and September 1956, four different typhoons struck the island. The most powerful of these was typhoon Emma with maximum recorded winds over 150 mph. Damage to military facilities alone totaled over $10 million (1956 US dollars), reducing the military capability of one of the most strategically important US military bases in the world to zero in less than 12 hours. The importance of the DoD weather forecast presence in WESTPAC proved to be invaluable, however. The weather warnings were communicated to a well prepared populace and the result is best summed up by an Army report which stated ". . . warning was adequate and all personnel displayed remarkable discipline and knowledge of prescribed procedure. As a result, there was minimum loss of life, personal injury and suffering."(Msg 10675 (U), CG RYCOM/IX Corps to CG AFFE/8A (R), 15 Sep 56.). In a more recent incident, the military installations on Okinawa remained in a state of emergency lockdown while in the highest condition of readiness for over 24 hours as they eye of Typhoon Man-yi clipped the southern end of the island in July, 2007 (18th Wing Public Affairs, July 14th). Many aircraft at Kadena had to be evacuated over a thousand miles away to Guam. Though significant power and water outages were reported, accurate weather warnings and the timely issuance TCCOR again prevented both loss of life and significant damage to Okinawa's many military assets.

Figure 4.   Airmen at Kadena Air Base, Japan, tow an F-15 Eagle into a protective shelter in preparation for Typhoon Man-Yi, July 12, 2007 (from http://www.af.mil/news/story.asp?id=123060525)

The authority for setting TCCOR in Okinawa is vested in the Commander of the 18th Wing of the U.S. Air Force at Kadena Air Base. The 18th Weather Squadron, also at Kadena, coordinates closely with JTWC and makes official TCCOR recommendations to the Commander. Due to the geographic location Okinawa adjacent to the warm waters of the northward flowing Kuroshio Current, it is not uncommon for tropical cyclones in the area to rapidly intensify with little warning and, in some cases, form directly over the island. For this reason, all DoD military installations on Okinawa remain in TCCOR 4 throughout the official WESTPAC typhoon season from 1 June to 30 November.

3. Sasebo, Japan

In June 1946, U.S. Fleet Activities Sasebo, Japan was established 485 miles northeast of Kadena on the northern end of Nagasaki prefecture. Today, the 854 acre base (Figure 5) serves as a logistical support hub to naval units across the WESTPAC and is home to eleven assigned US Navy ships and a community of approximately 6000 personnel and their families. The base is unique in that it is home to Commander, Amphibious Squadron ELEVEN, the only forward deployed amphibious squadron, as well as forward deployed mine countermeasures units. The two dry docks and multiple heavy lift cranes located at the port also enable Sasebo to provide major hull repairs and other critical services to the many ships that frequent the area.

Figure 5.   The rugged local terrain and naturally enclosed waterways at Sasebo, JA
afford vessels protection from typhoon wind and waves.

The Typhoon Haven's Handbook states that during a sixty year period from 1945 to 2005, 149 tropical cyclones passed within 180 NM of Sasebo, an average of just under 3 per year. Just over a third of those storms were of typhoon strength. This decreased frequency of annual typhoon encounters does not diminish the importance of timely and accurate weather warnings, however. Because of the mountainous surrounding topography and the naturally enclosed harbor, Sasebo has long been considered a very good "typhoon haven."   This attracts a multitude of vessels seeking shelter from throughout the Sea of Japan, Inland Sea, and East China Sea, well in advance of any approaching storm (Figure 6). This often complicates the movement of larger military ships and crowds the limited harbor space. Additionally, wind and wave conditions affecting moored and anchored ships can be very different depending on the storm's closest point of approach (CPA) and whether the storm passes to the east or west. Although the harbor is a haven, damage has been sustained in the past by ships that were improperly positioned relative to the storm conditions. Therefore, the local military authorities are heavily reliant on accurate warnings which allow them ample time to maneuver units and best secure for the threat. The base itself is also relatively small

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compared to others in WESTPAC and the slightest damage from a passing storm can have longer lasting impacts on the operational readiness of facilities and assets located there (Tyler, 2004).

Figure 6. The USS Patriot (MCM-7) is secured in a wet berth to prevent damage from the approaching Typhoon Shanshan, Sept. 16, 2006 (from http://www.navy.mil/list_single.asp?id=39274)

TCCOR levels IV - I for Sasebo are recommended by the Naval Meteorology and Oceanography Command at Yokosuka, Japan and set by the Commander, Naval Forces Japan (CNFJ). TCCOR I Caution, TCCOR I Emergency and TCCOR All Clear are set by the Commander, Fleet Activities, Sasebo (COMFLEACT). Unlike Guam and Kadena, the base remains in an "All Clear" status until an approaching storm warrants the issuance of a higher level TCCOR. Of the four sites studied for this thesis, Sasebo experiences the fewest tropical cyclones per year with a mean occurrence of 2.44 per year passing within 180 nm of the base (NRL, 2008).

4. Yokosuka, Japan

Yokosuka, Japan is home to a number of significant U.S. Navy commands, including the U.S. Seventh Fleet, Naval Forces Japan, Destroyer Squadron Fifteen, and Submarine Group Seven, which make up the Forward Deployed Naval Force (FDNF) Japan. The city is located at the entrance to Tokyo Bay in one of the most densely

populated regions in the world. Due to the large fleet presence, the base is undoubtedly the most strategically important American military site in the Western Pacific. The only forward deployed U.S. aircraft carrier, along with 17 other fleet vessels, are based out of Yokosuka alongside a number of Japanese Military Self Defense Force (JMSDF) units. The port is also home to the largest naval ship repair facility and the largest Fleet Industiral Supply Center in the region (Figure 7) providing over half of the U.S. fuel assets for the Pacific. Nearly 30,000 U.S. military and civilian personnel are employed at the 55 tenant commands at Yokosuka. Other nearby military installations on the Kanto Plain surrounding Tokyo include the Naval Air Facility Atsugi, Yokota Air Base, Camp Zama Army Post, and the USMC Combined Arms Training Center at Camp Fuji.

Figure 7.   The protective dry-docks and extensive port facilities at Yokosuka, JA support a variety of vessels from the U.S. SEVENTH FLEET and the JMSDF (from www.yokosukanavyball2007.com).

Less than 100 miles outside of Tokyo Bay, the Kuroshio Current flows along the southern coast of Japan and forms the northern periphery of the most active typhoon breeding ground in the world. Though the sheltered port is considered a typhoon haven, ample time and accurate warnings are still necessary for the many ships in the harbor to adequately prepare for an approaching storm. Because of Yokosuka's location in the midlatitudes, the majority of storms that affect the base have already undergone

recurvature and are accelerating to the northeast, often at speeds in excess of 20 mph. During a sixty year period from 1945 to 2005, 158 tropical cyclones passed within 180 NM of Yokosuka, roughly one third of which had attained typhoon strength. Storms in this region often interact with midlatitude weather features and can re-intensify without warning when passing over the warm waters of the Kuroshio, further complicating the challenge for forecasters. Additionally, the number of high value assets that are often within the harbor further adds pressure to get the forecast right and allow plenty of preparation time for safeguarding of the ships. In 2004, for example, the Seventh Fleet flag ship was damaged when a nearby vessel broke free and collided with her in the harbor due to stronger than anticipated winds associated with a passing typhoon.

Like Sasebo, the TCCOR authority for Yokosuka and nearby Atsugi is the Commander, Naval Forces Japan. The Admiral receives recommendations from the Naval Meteorology and Oceanography Detachment at Yokosuka and remains in an "all clear" status until a tropical cyclone warrants the setting of TCCOR IV or higher. TCCOR authorities for other DoD facilities and installations on the Kanto plain and elsewhere in Japan are defined below in Table 2.

Table 2.   2008 TCCOR Authorities for DoD installations in Japan

Commander 18th wing, Kadena AB	18 OSS/OSW	Okinawa – all DOD installations
Commander, Naval Forces Japan (CNFJ)	NPMOC Yokosuka	Yokosuka Area Yokosuka, Yokohama, Iwo Jima (U.S. DoD present) Sasebo Area Sasebo, Yokose POL Depot and Tsushima Communications Site
Iwakuni Commanding Officer	MCAS Iwakuni Weather Office	Iwakuni Area Iwakuni, Communications Sites (Sofu, Rokko, Haigamine), Ammo Depots (Akizuki, Hiro, Kawakami), Kure Pier No. 6
Commander, US Forces Japan (USFJ)	20 OWS	Kanto Plain Yokota AB, Camp Zama, Sagami Depot, NAF Atsugi, Camp Fuji
Commander, 35th Fighter Wing, Misawa AB	35 OSS/OSW	Misawa Area Misawa, Hachinohe POL Depot

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II. BACKGROUND

A. FORECASTING TCCOR

One of the most critical responsibilities of DoD forecasting centers in the WESTPAC is advising local military Commanders to set TCCOR in order to prevent damage and to save lives as a tropical cyclone approaches. Though it is expected that storms will impact military operations and inevitably cause damage and possibly loss of life every year, setting every level of TCCOR is a costly decision for the Commander in terms of time, money and operational readiness. Many factors such as the local terrain, civilian infrastructure, type of military assets (ships, aircraft, etc.) and ongoing mission critical operations conducted at each installation determine vulnerabilities that military Commanders must consider when deciding when and how to brace for a storm. U.S. Navy ships, for example will almost certainly sortie out of the exposed harbors in Guam and Okinawa as a storm approaches rather than from the well protected harbors and anchorages in Sasebo and Yokosuka. Air Bases such as Kadena and Andersen are focused on impacts to flight operations and the protection of aircraft in hangars. The forecaster's challenge is to use every asset available in order to provide an accurate timeline of events, including onset and offset of defined wind thresholds, to the local TCCOR authority. This process starts well before the tropical cyclone ever makes landfall and involves a great deal of coordination between the JTWC and the local weather center responsible for recommending TCCOR. With each 6-hourly warning from JTWC, the anticipated TCCOR timeline is adjusted to reflect the latest changes in the tropical cyclone's forecast track, speed of advance (SOA), or intensity. In Yokosuka, the Tropical Cylclone Watch Officer is responsible for developing periodic briefs and updates on the storm as outlined in Figure 8. In 2007, the JTWC attempted to aid the forecaster and standardize this process by creating a computer utility that uses JTWC official warnings to determine TCCOR timeline.
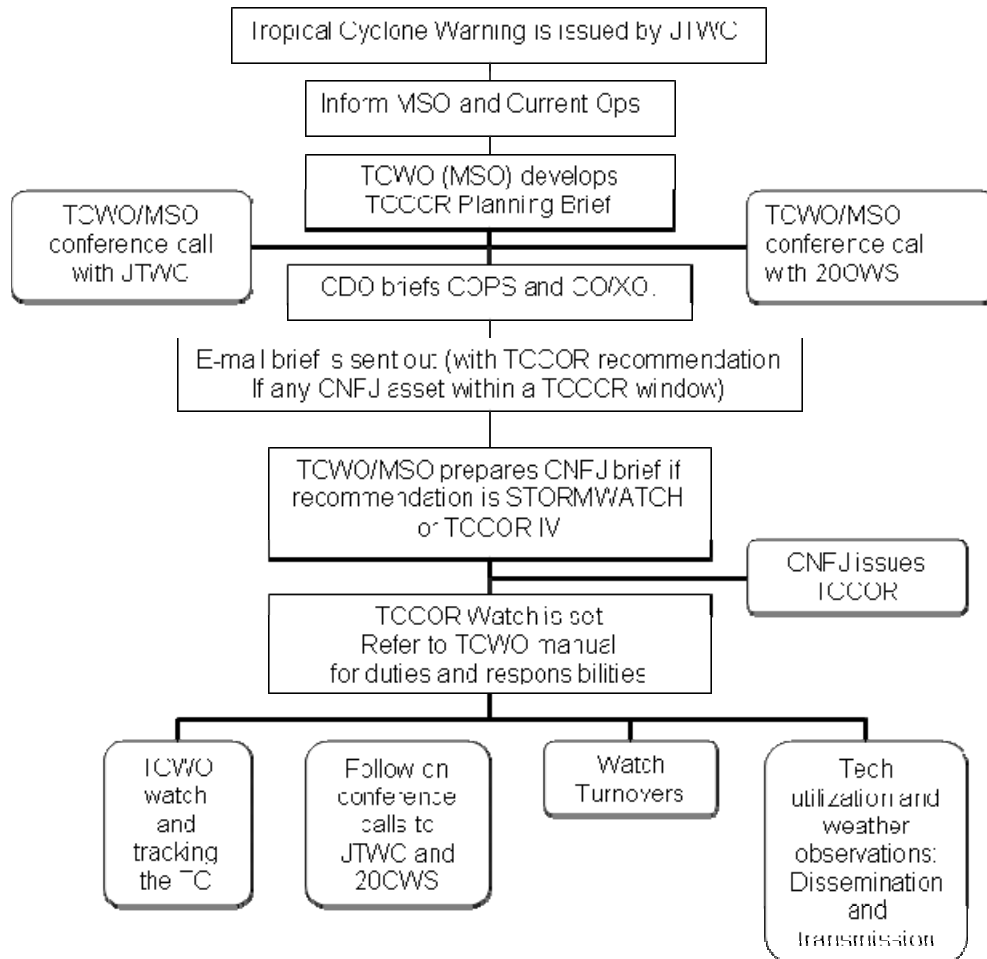
Figure 8.   The TCCOR decision flow chart for Yokosuka, JA (from CDO SOP #10).

1.   The Tropical Prediction Utility

Prior to 2007, watch-standers at respective forecast centers were trained to create timelines for TCCOR authorities by hand using official warning information, time distance calculations on paper, and forecasting knowledge of the local area. When JTWC assumed responsibility for TCCOR recommendations for CNFJ installations in 2007, a spreadsheet-based Tropical Prediction Utility (TPU) was developed to ensure a level of TCCOR timeline standardization and to facilitate the creation of graphical images for briefing purposes.   The TPU ingests specially formatted 6-hourly JTWC warning messages and produces a graphic file which can then be displayed on the Joint METOC Viewer (JMV), which is a web based utility designed by the Fleet Numerical

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Meteorology and Oceanography Center (FNMOC), Monterey to graphically create and export a variety of environmental products to regional METOC centers. The resulting TPU graphic (Figure 9) is similar to the JTWC warning graphic (Figure 10) in that it depicts the current tropical cyclone center location and forecast positions at 12, 24, 48 and 72 hours but the wind radii and ship avoidance area are replaced by representative TCCOR boundaries. The distance from the nearest boundary to the location of interest is then calculated within JMV and, when compared to the forecast SOA, a time for setting the next appropriate TCCOR can be determined. The TPU is not intended for operational use, only as additional guidance for the forecaster.
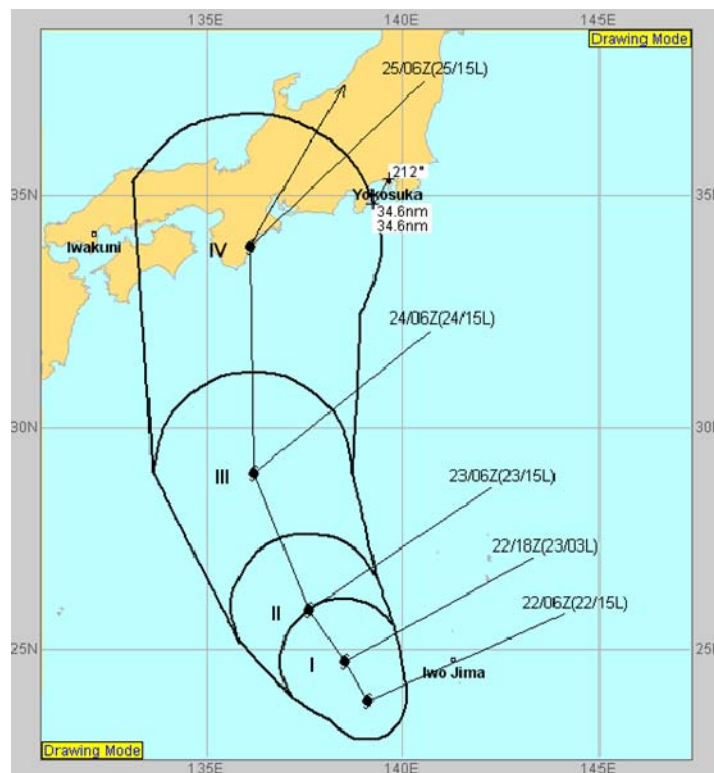

Figure 9.   TCCOR boundaries produced by the TPU for Typhoon MAWAR in August 2005.
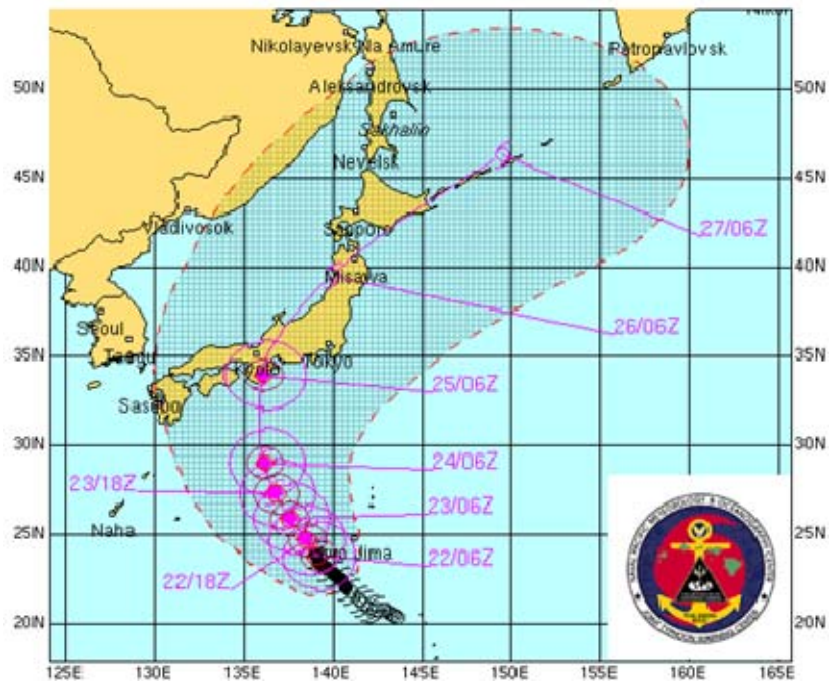
Figure 10.   The JTWC warning graphic for Typhoon MAWAR.

B.   PROBABILISTIC FORECASTING AT JTWC

Traditionally, tropical cyclone forecasts have been deterministic in nature and lacked the ability to quantify uncertainty.   This is a result of attempting to predict conditions using "categorical" forecasts, which imply 100 percent certainty.   With the complexities involved in forecasting for tropical cyclones, this method is prone to error. Rarely does the storm move along the exact forecast track line or move at the exact forecast speed.   This forecast error grows with each time step (TAU) into the forecast period and, in the case of tropical cyclones in the Western Pacific, is often in excess of 500 mi. by five days.   In an effort to communicate this inherent error to customers, the JTWC includes an "area of uncertainty" on official warning graphics.   This shaded region surrounding the official forecast track (see Figure 10) is calculated by adding the JTWC 5-year running mean forecast track error to the forecast 35 knot wind radii at each time and represents a 70% chance of experiencing gale force winds in the next 5 days (JTWC, 2008).   It does not, however, take into account parameters such as uncertainties in the forecast size or intensity of the storm and gives no indication of how well the dynamic

aids agree. Though the occurrence of destructive winds from a tropical cyclone is relatively rare for any particular location, the danger is very real and decision makers could potentially benefit by understanding the uncertainty in forecasts and assessing the associated risk.

1.   The Wind Speed Probability Model

The motivation for producing the wind speed probability model is to provide users an estimate of the uncertainty associated with the deterministic forecast. As Jarrel (1987) states, the wind speed probability product was a proven concept in the early 1980's and was available for most areas of the world by the end of that decade. In recent years, however, the potential benefits of such a product have received an increasing amount of attention and efforts have been made to improve it using faster, more capable technology. One of the most significant of these improvements was introduced by Gross et al. (2004) and involved using a different statistical sampling technique, known as the "Monte Carlo" method, to account for uncertainties in storm size and intensity in addition to the forecast track.

This method of sampling was designed to take into account the effect of serial correlation. A sample of random numbers is generated from a reference distribution and the properties of the resulting sample are observed and applied as perturbations to the next generated sample. In this manner, the forecast track that was to the left of actual storm track at the 24-hour position and, thus, tended to be left of track throughout the forecast period could be accounted for (Gross et al., 2004).

Though still under development, the JTWC currently produces wind speed probability graphics for the Western North Pacific basin. By randomly sampling historical 5-year track and intensity errors and determining size variations from climatology and persistence data, 1000 different forecast tracks are produced. The swaths of the associated 34-, 50-, and 64-kt wind thresholds are calculated for each track and summed each time they occupy specific .5 latitude/longitude geographic grid points. The totals are then divided by the number of tracks to depict the cumulative probability throughout the forecast period that max sustained surface winds will meet or exceed

aforementioned thresholds. By combining the reliability of the deterministic solution in the near-time forecast with a better understanding of the probabilistic uncertainty in the long-range forecast, users will be better prepared to make critical decisions.
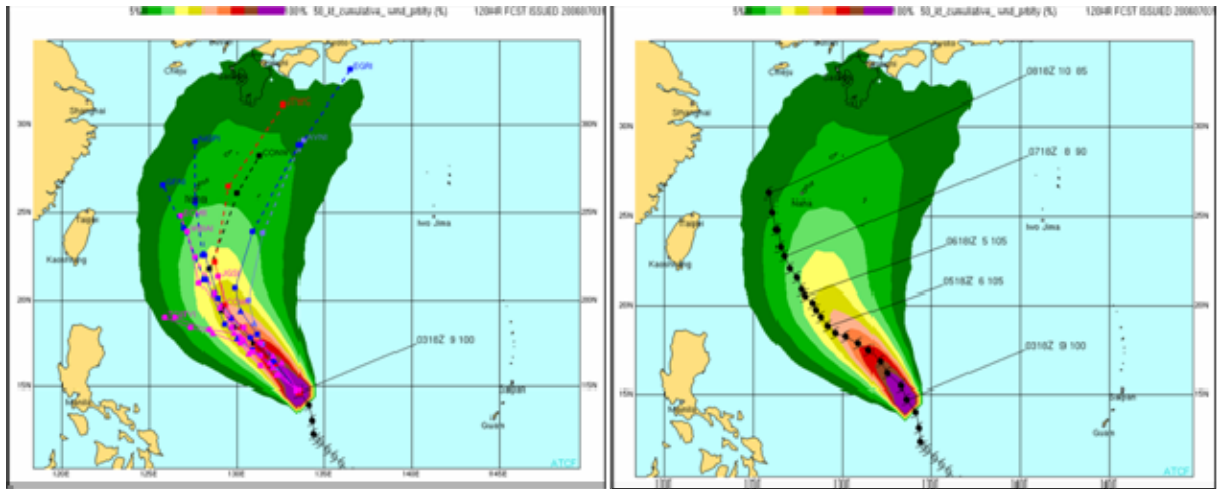

Figure 11.   The JTWC wind speed probability product with overlayed dynamic aids (left) and the best track (right).

Figure 12.   The text version of JTWC Wind Speed Probability Product.

III. METHODOLOGY

A. DATA

1. Data Sources

Data for this thesis were collected from the 2002 – 2007 WESTPAC typhoon seasons. Over the course of this six-year period, 171 tropical cyclones occurred in the region, equating to an average of 28.5 cyclones per year. According to the 2007 Annual Tropical Cyclone Report produced by JTWC, 2004 was by far the most active year with a total of 32 storms compared to a minimum of 25 in 2005. Obtaining accurate historical records detailing the timeline of TCCOR settings at each of the four aforementioned DoD installations for this study was a challenge and in some cases only partial timelines could be obtained. Weather observations were obtained from the Air Force Combat Climatology Center (AFCCC) as well as from media releases and storm reports. These timelines were then compared to timelines created from the TPU and to the archived best track files within the Automated Tropical Cyclone Forecast (ATCF) system maintained by JTWC.

2. Historical TCCOR Timelines

Compiling a data set of actual TCCOR timelines for each of the four installations studied in this thesis was critical to compare them to the recommendations obtained from the TPU. However, this proved to be a significant challenge because most of these data were simply recorded in log books and not maintained in any kind of data base for any of the four sites. Detailed storm reports that include times when each TCCOR was set have only recently been standardized. To complicate matters, the responsibility for recommending TCCORs at sites such as Sasebo and Yokosuka has shifted between NPMOC Guam, NPMOC Yokosuka and NMFC Pearl Harbor since 2000. Sources used to obtain many of the timelines include various media archives, storm reports when available, official Navy message traffic, and copies of e-mail communications between various forecasting agencies throughout the Pacific. Altogether, records from 33 separate

storms were examined, which resulted in 42 partial or complete TCCOR timelines (Figure 13) at one or more of the four installations.
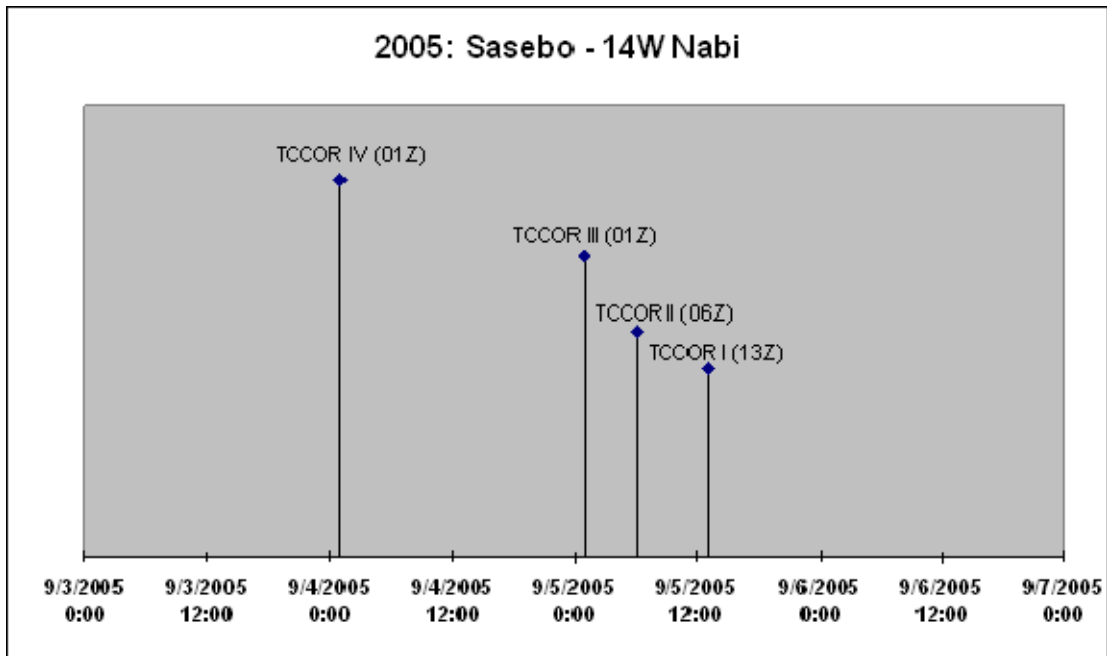
Figure 13.   Representative TCCOR timeline created for Typhoon Nabi as it approached Sasebo, Japan.

3.   Wind Observations

Wind observations were also added to the TCCOR timelines for verification. In cases where 50-kt sustained winds did not occur, the time of the maximum sustained wind (MSW) was used as shown in Figure 14. The MSW for each TCCOR timeline were then placed in one of three Wind Verifying Categories (VCAT) based on intensity shown in (Table 3).

Table 3.   The maximum sustained winds (MSW) categories.

msw	VCAT
<34 kts	1
34 - 49 kts	2
>50 kts	3
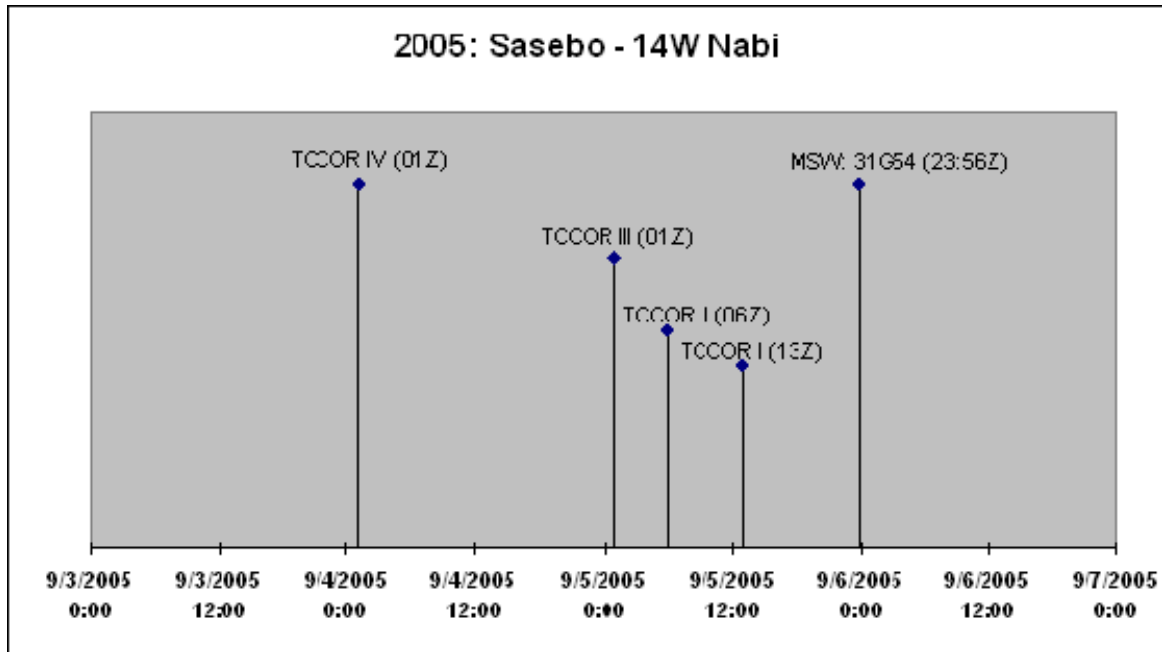
Figure 14. As in Figure 13, except with the observed maximum sustained wind during storm passage plotted.

4. TPU predicted TCCOR

Using the TPU, predicted TCCOR times were retroactively created for every storm that affected the four sites. These date time groups (dtgs) were then plotted on the aforementioned historical TCCOR timelines for comparison (Figure 15). The time difference between the historical TCCOR times and the predicted TCCOR times (Δt) could then be calculated using the equation,

$$\Delta t = TPU\ t - TCCOR\ t \qquad (1)$$

where a positive (+) value indicates the TPU was set earlier than the historical TCCOR (Figure 15).
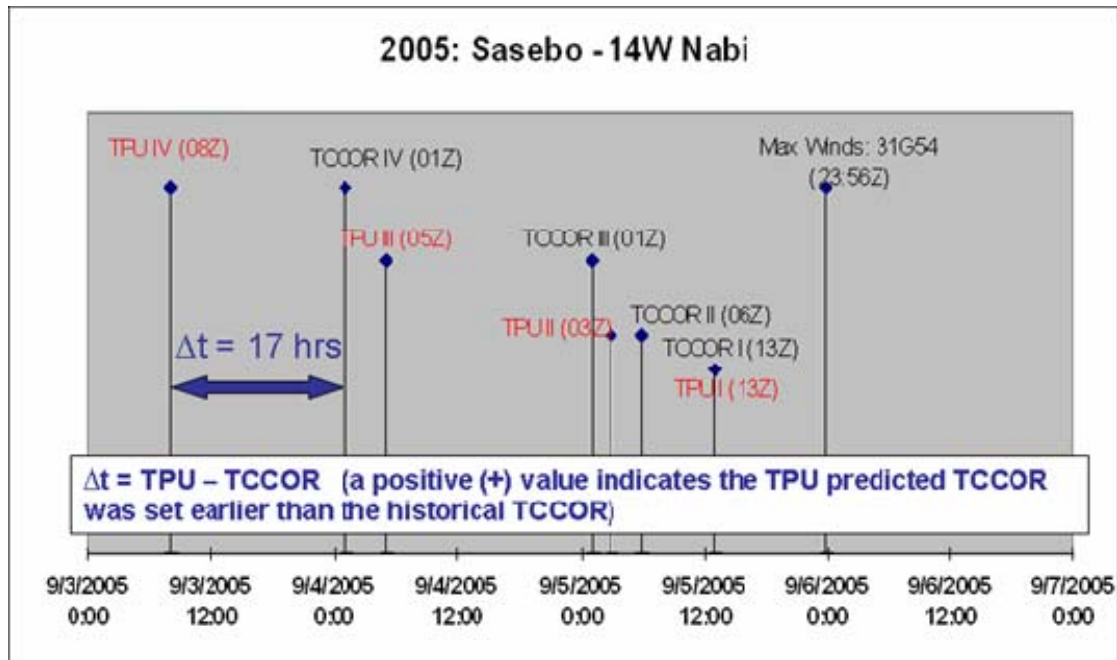
Figure 15.   The time differences between each TCCOR and TPU settings.

The total duration that each of the historical TCCOR and TPU predicted TCCOR lasted were also determined from the timelines (Figure 16). The differences in these durations were then calculated (Figure 17) and compared to the Δt values using the equation:

$$\Delta \text{ Duration} = \text{TPU duration} - \text{TCCOR duration} \qquad (2)$$

A positive (+) Δ Duration value indicates that the TPU lasted longer than the historical TCCOR.
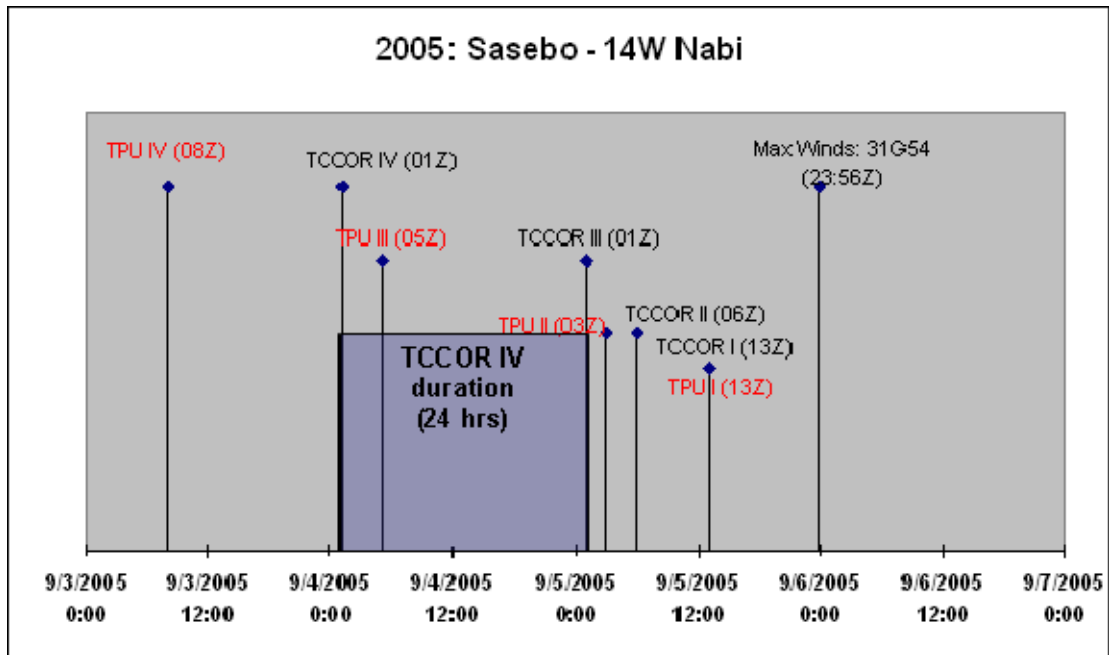
Figure 16.   The duration of TCCOR setting timelines.
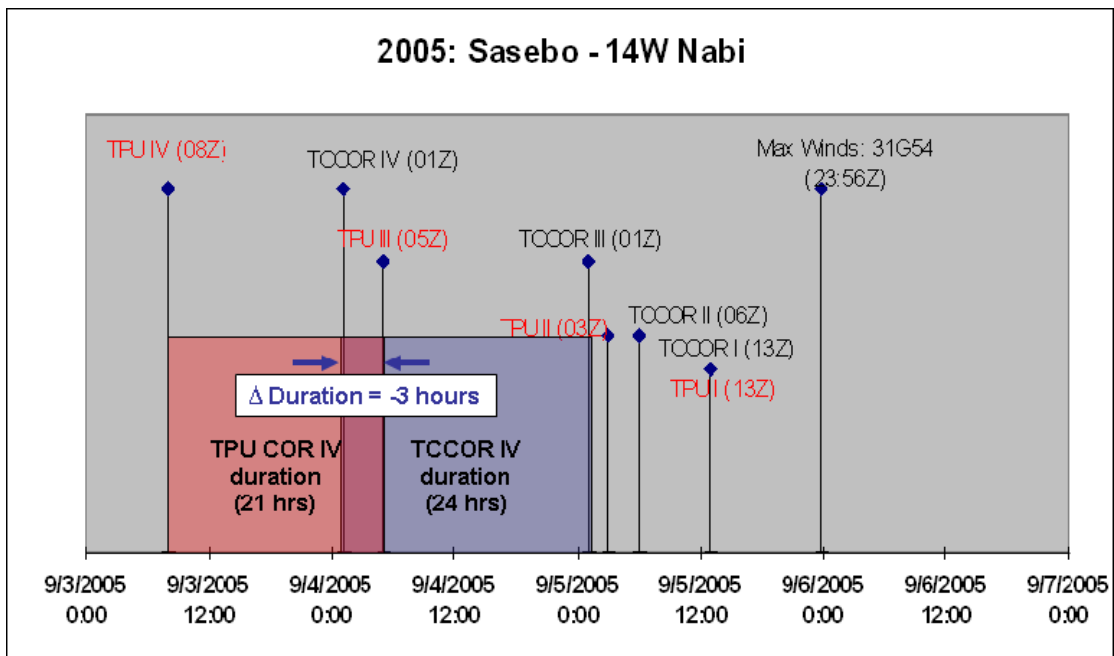
Figure 17.   The duration difference between TCCOR and TPU settings.

5.   Time to Maximum Sustained Wind

For every predicted and historical TCCOR setting, the time to the maximum sustained wind (TMSW) was determined. These times were then binned into categories (TMSW CAT) by determining how closely they aligned with the definition of the respective TCCOR. For example, TCCOR III is set when destructive winds are anticipated in approximately 48 hours. If the TMSW was within +/- 3 hours of 48, it was assigned a "0". If it was outside this range, it was assigned a +/- 1 or +/- 2 based on how many TCCOR categories "early" or "late" the maximum sustained winds were actually observed (Table 4).

Table 4.   A sample of how the TCCOR III TMSW were categorized based on how "early" or "late" the maximum sustained winds actually occurred.

TCCOR III tmsw (hrs)	III tmsw CAT
29	-1
51	0
55.8	1
46	0
53.5	1

6.   Wind Speed Probability Model Data

For each of the TPU predicted and historical TCCOR times plotted on the timelines, the corresponding 50-kt wind speed probability values were generated using the NRL wind speed probability model. Graphical depictions of these probabilities were also created and Figures 18 – 20 show a progression of comparisons between the TPU graphics and the corresponding wind speed probabilities as Typhoon Nabi approached Japan in 2005.
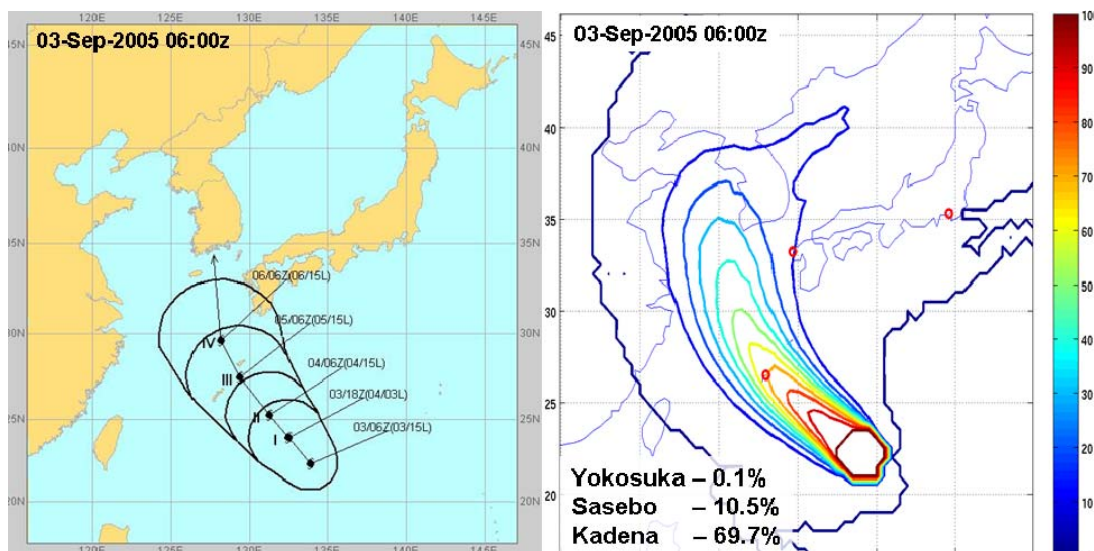
Figure 18.   Progression of TPU settings (left column) and wind speed probability (right column) associated with Typhoon Nabi at 06:00 UTC 3 September 2005.
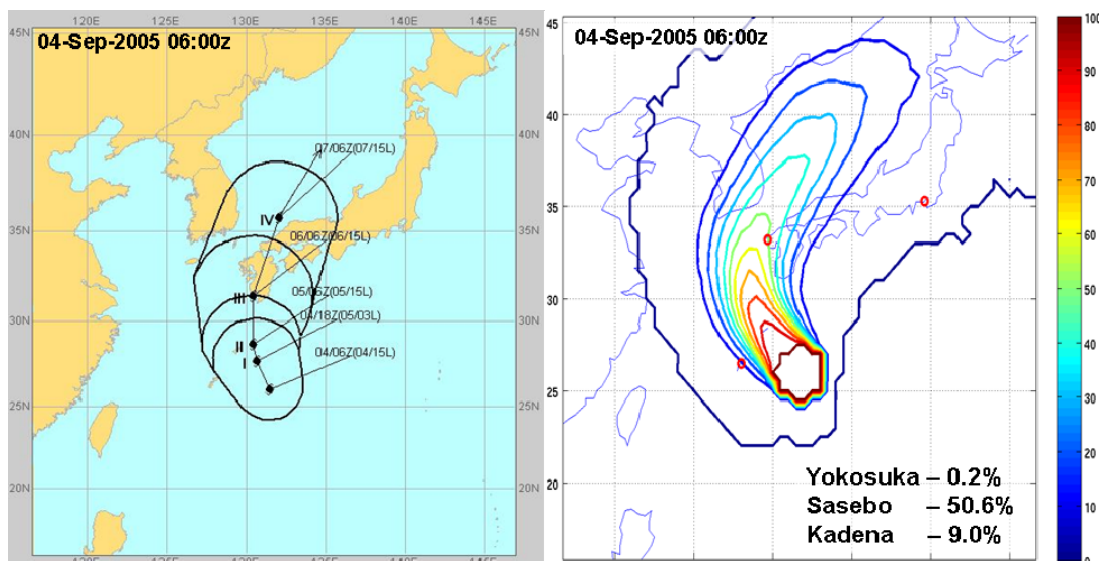
Figure 19.   As in Figure 18, except for 06:00 UTC 4 September 2005.
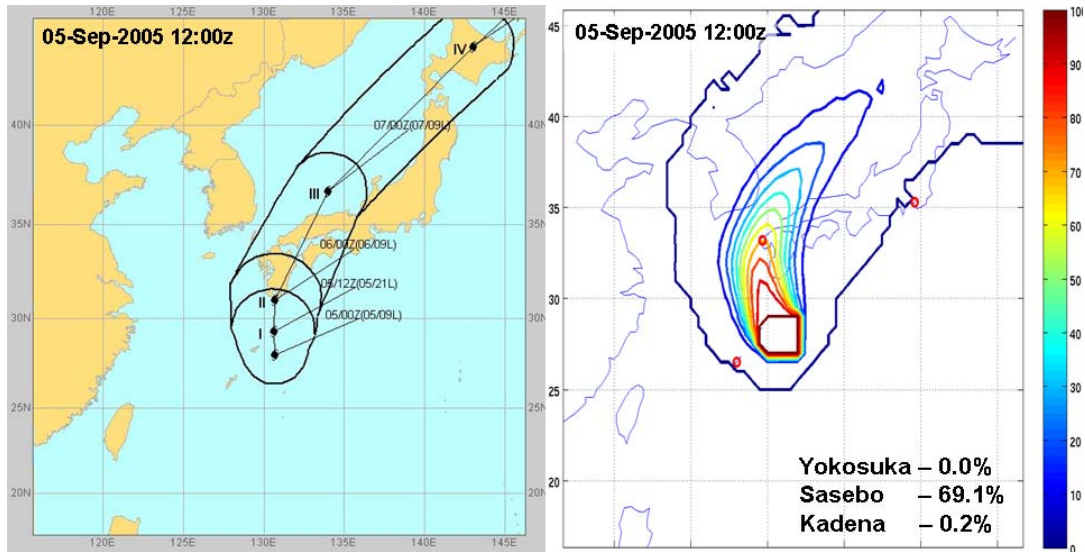
Figure 20.   As in Figure 18, except for 12:00 UTC 5 September 2005.

As with the wind observations, sorting the resulting wind probabilities into categories (PCAT) facilitated statistical analysis of the data. Because the probabilities ranged from 0 to 100%, the data could easily be split into thirds or "terciles" as shown in Table 5.

Table 5.   The wind speed probability categories for each TCCOR.

Wind Prob.	PCAT
<34%	1
34 - 66%	2
>66%	3

In addition to calculating the wind speed probabilities for every time a TPU predicted or historical TCCOR was set, probabilities were also calculated at 12-, 24-, 48- and 72-hours prior to the actual observed time of maximum sustained wind (TMSW) for determining the utility in the wind speed probability due to defining each TCCOR category.

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## B.	STATISTICAL ANALYSIS

### 1.	Scatter Plots and Histograms

Scatter plots are a simple way to visually demonstrate the relationship between two variables by displaying data points on a two-dimensional graph. These plots are especially useful when the relationship between variables is not perfect and may not be obvious from the spreadsheet alone. Some useful properties that can be determined from scatter plots include the overall strength of the relationship between two variables, the shape of the relationship (straight line or curved), the direction of the relationship (positive or negative), and the presence of outliers. In this thesis, scatter plots were useful in determining the relationship between two variables, such as Δt and Δduration, or the dependence of the wind probability for each TCCOR on time.

Histograms are created by separating values from a data set into predetermined bins or categories. The number in each bin is then representative of the frequency of occurrence, or count, in that particular category. The shape of the resulting distribution can give information about the median, standard deviation, and variance of the population. In this thesis, histograms were used to demonstrate trends between TCCOR and categorized wind speed probabilities.

### 2.	Testing for Differences in Mean

Figure 21 shows three pairs of distributions, each with the same average value, or mean, but with obvious significant differences between the samples. The distributions in the "low variability" case, though similar in shape, have very little overlap and therefore are considered statistically different. The amount of overlap in the "medium variability" case is larger but the distributions are still distinguishable from one another. The high variability case, however, has a large amount of overlap making it difficult to distinguish unique characteristics between the two distributions.

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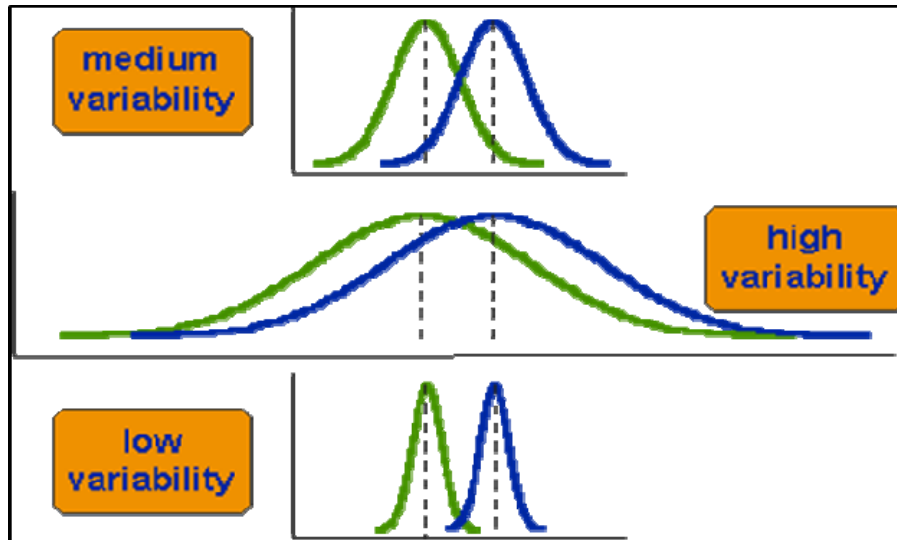
Figure 21.   Three pairs of statistical distributions with the same mean but different degrees of variability (from Trochim, http://www.socialresearchmethods.net/kb).

For the purposes of this thesis, it was often necessary to group the categorized parameters from each timeline and compare the means in order to determine any significant trends or differences. A common method used to measure the difference between two populations of data is the t-Test. The t-Test statistic (T) is a function of the differences between two sample means and takes into account the characterstics of the distributions,

$$T = \frac{\overline{X}_1 - \overline{X}_2 - \mu_0}{\sqrt{\dfrac{S_1^2}{n_1} + \dfrac{S_2^2}{n_2}}}$$

where $\overline{X}_1$ and $\overline{X}_2$ are the means of the two samples, μ_0 is the hypothesized difference between the two means, S_1 and S_2 are the sample standard deviations and n_1 and n_2 are the numbers of members in each sample. For this study, the t-Test was evaluated using a confidence level of 95%, which means the test will be in error no more than 5% of the time.

3. Contingency Tables

A contingency table is used to record and demonstrate the relationship between two or more categorical variables. This kind of table can also be used as a representative scorecard for predictions or forecasts and can give some sense of the performance in terms of "Hits", "Misses" and "False alarms." Table 6 shows a 2x2 contingency table where "A" represents the number of entries where observations matched forecasts conditions, or Hits, "B" represents forecasts that did not validate, or False Alarms, "C" represents no-event forecasts that correspond to observations of the event, or Misses, and "D" represents no event forecasts where no event occurred, or correct rejections.

Table 6.   A 2x2 contingency table comparing forecast and observed events.

2X2 Contingency Table		Event Observed	
		Yes	No
Event Forecast	Yes	A	B
	No	C	D

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IV. ANALYSIS AND RESULTS

A. INTRODUCTION

The goal of this thesis was to evaluate the TCCOR prediction process over the past several years and determine if guidance from the objective TPU and the wind speed probability model could potentially add value to the process. Due to the uniqueness of the four locations selected for study, some variations existed in the application of TCCOR. As discussed earlier, Guam, remains in a TCCOR IV status year round and installations on Okinawa such as Kadena observe a "seasonal TCCOR IV" during the time of year when typhoons frequent that region of the WESTPAC. Because of this inconsistency, which results in a low number of TCCOR IV events, it was of little use to analyze TCCOR IV statistics in this thesis. Additionally, TCCOR that were unique to only the U.S. Forces Japan (USFJ) area of responsibility, including TCCOR I Caution, I Emergency, I Recovery, and Storm Watch were not included.

Various parameters collected for TCCOR III – I for 42 separate cases from the 2002 – 2007 typhoon seasons were analyzed, including Δt and Δduration, the wind probabilities at each TCCOR and TPU predicted TCCOR, the wind probability categories and time to max sustained winds (TMSW). Additionally, a contingency analysis and probabilistic comparison of hits, misses, and false alarms for wind probability categories and wind verifying categories was conducted.

B. ANALYSIS AND RESULTS

1. Timeline Parameters

To determine the relationship between Δt and Δduration, scatter plots (Figures 22 and 23) were produced for TCCOR III – I with Δt plotted as the independent variable. A positive relationship between Δt and Δduration is evident for both TCCOR III and TCCOR II. Similar results were obtained for TCCOR IV and TCCOR I though each consisted of fewer data points. The plots indicate a proportionality between how much

earlier the TPU predicted TCCOR to be set compared to the historical TCCOR and an increased difference in the durations of the respective TCCOR. Also of note is that for the majority of the cases, Δt is positive, indicating that the TPU guidance is, on average, set earlier than the historical TCCOR. The positive relationship between Δt and Δduration is interpreted as a measure of the impact of uncertainty in the forecasts used to drive the TPU model. Recall that the official forecast is used to define the TPU setting times. The fact that actual TCCOR settings are made later indicates that the delay could be due to uncertainty in the forecasts and TPU timelines. Therefore, TCCOR settings may be set in a more conservative manner than defined by the objective TPU process.
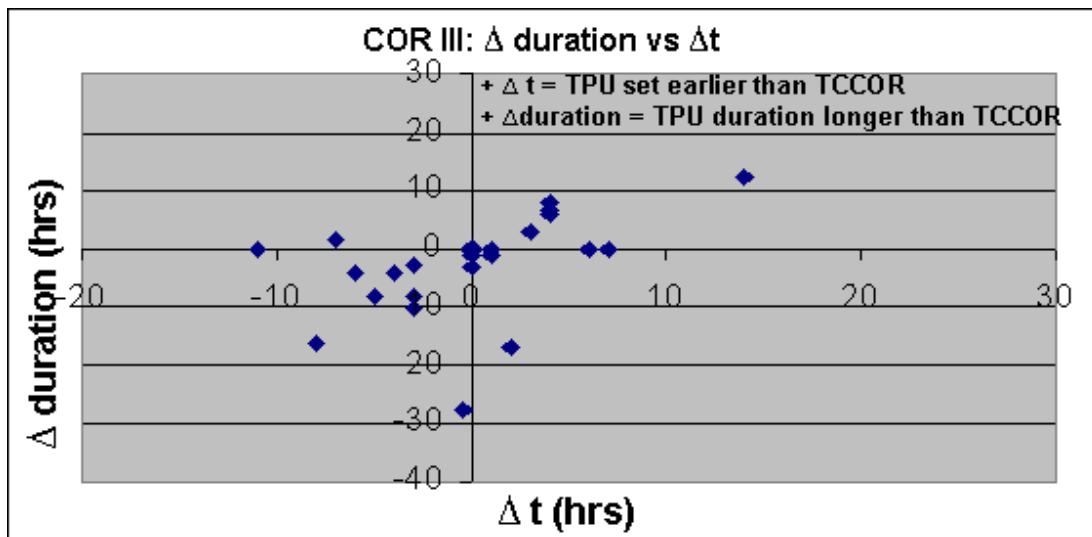
Figure 22.   TCCOR III scatter plot of Δduration vs Δt.
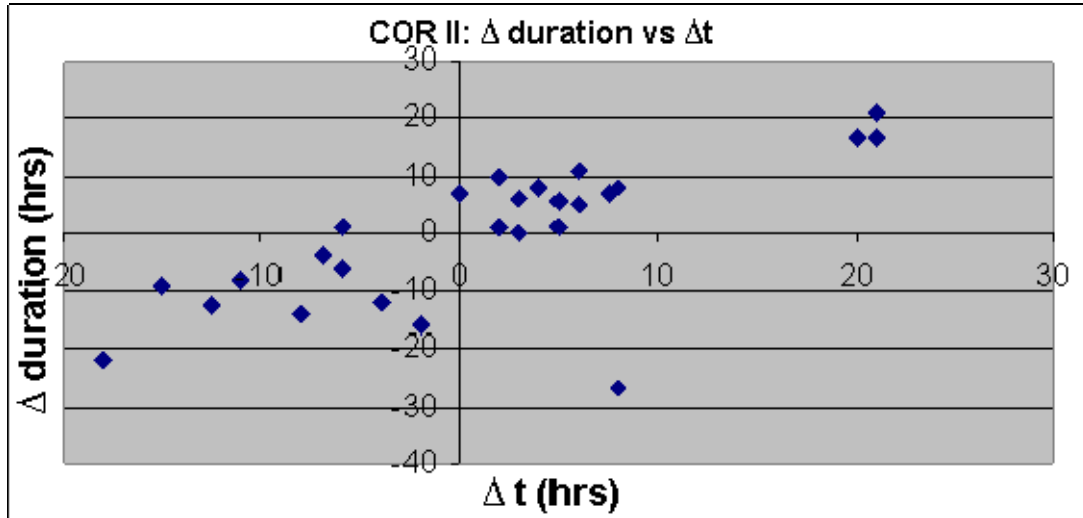
Figure 23.   TCCOR II scatter plot of Δduration vs Δt.

2.   Wind Speed Probability Categories and TCCOR

Histograms of the wind speed probabilities were created as a means of comparing the distributions for each TCCOR (Figure 24). The lower, middle, and upper terciles are annotated on each plot and reveal an increasing trend in the probabilities as the TCCOR elevate from III to I. Using the tercile benchmarks as examples, the potential value of using probabilistic thresholds is demonstrated as an aid in the setting of each respective TCCOR.   An in depth study of a larger sample of cases would be needed, however, before these thresholds could be defined.
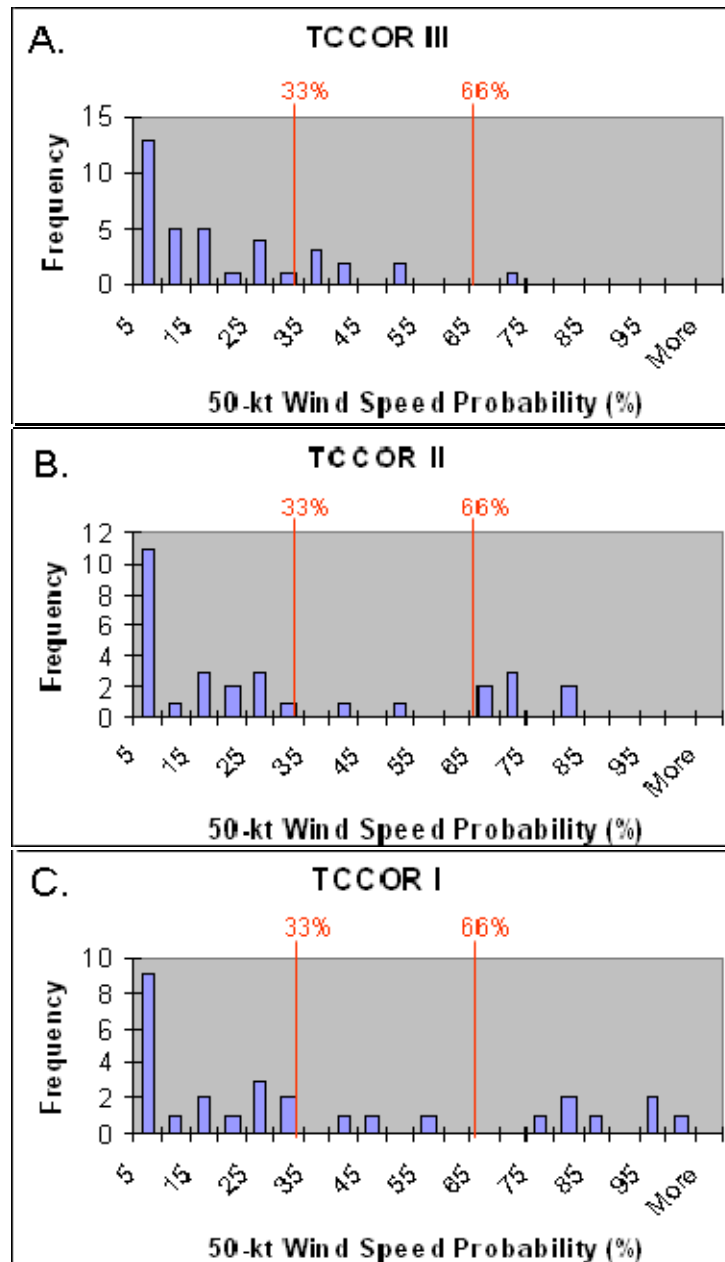
Figure 24.   Wind speed probability histograms for TCCOR III – I.

Two distinct trends were evident when the count values for the TCCOR III – I wind speed probability terciles were plotted (Figure 25). For low probabilities (PCAT 1), the counts decreased as the TCCOR were elevated. For high probabilities (PCAT 3), the counts for elevated as the TCCOR settings increased.
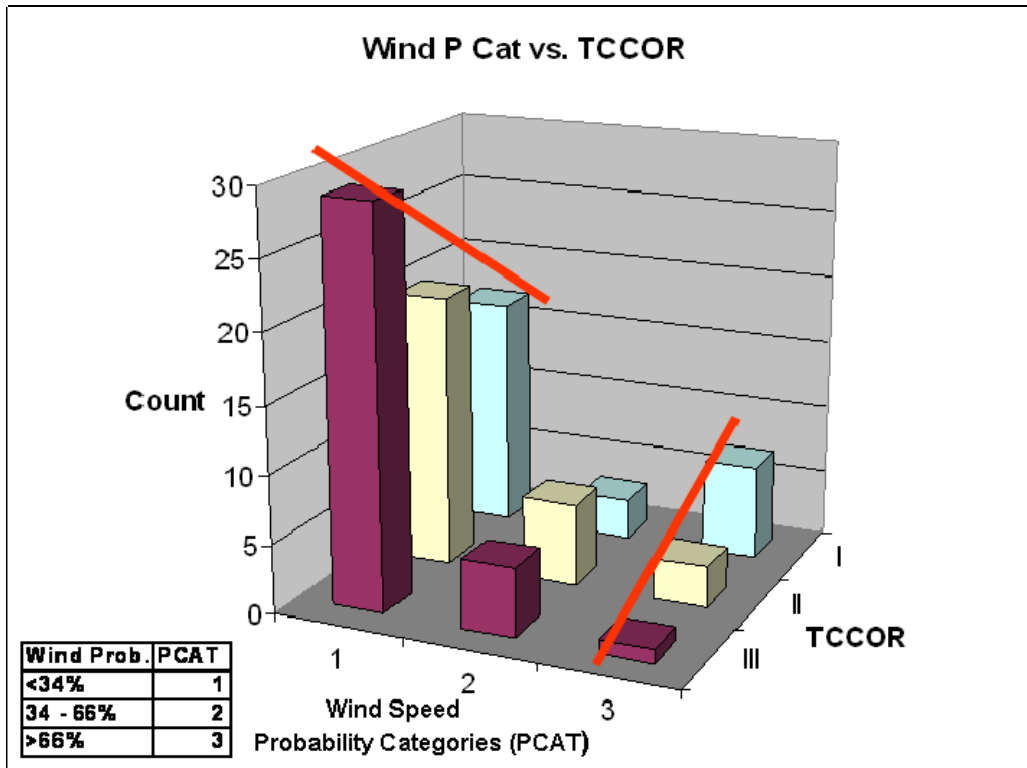
Figure 25.   The plot of Wind Speed Probability Categories (PCAT) vs. TCCOR with the significant trends for PCAT 1 and PCAT 3 annotated.

Therefore, as one would expect to incur fewer elevated TCCOR settings when wind speed probabilities were consistently in the lower tercile (low probability). Conversely, if the wind speed probabilities were in the upper tercile (high probability), one would expect an increased likelihood of experiencing destructive winds and, hence, an increased number of elevated TCCOR cases. These trends were also consistent when the predicted TCCOR from the TPU were analyzed in the same manner.

3.   Wind Speed Probabilities and Observed Winds

The X-Y scatter plots of the wind speed probabilities and the time to maximum sustained winds (tmsw) for TCCOR III – I are displayed in Figure 26. The vertical red line on each plot represents the time to the expected onset of destructive winds per the respective TCCOR definitions. The plots reveal a decrease in the standard deviation about the mean and an increase in wind speed probability values as the TCCOR elevated from III to I.
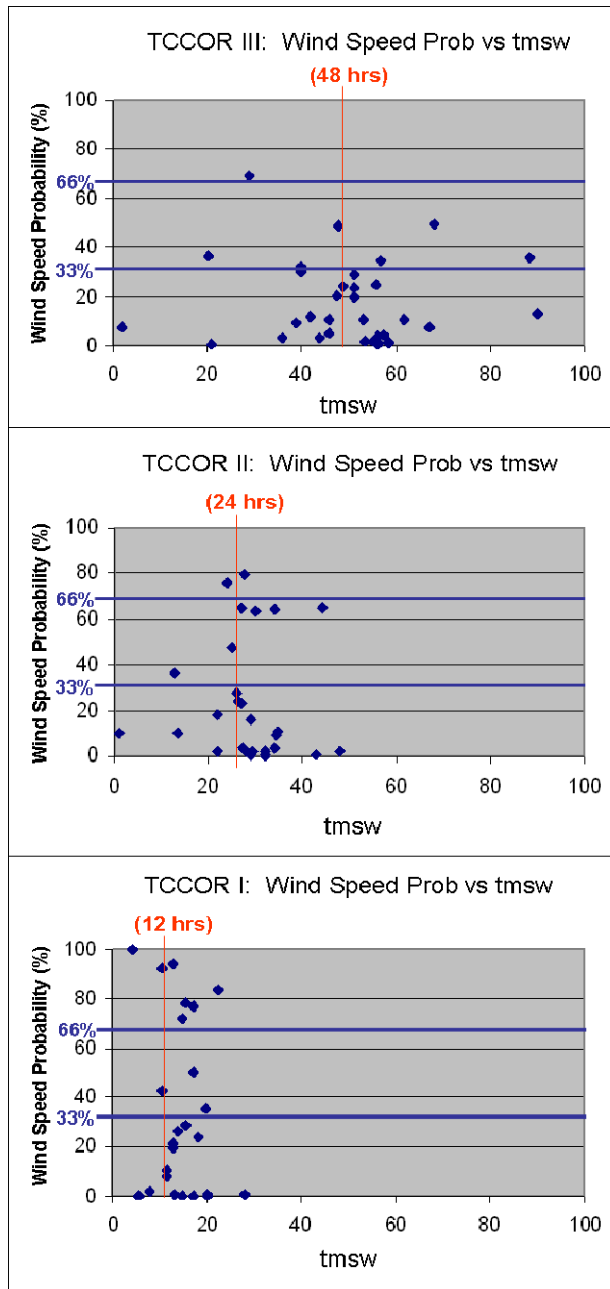
Figure 26.   The scatter plots for Wind Speed Probabilities vs. the TCCOR III–I tmsw.

Another obvious feature of each plot is the tendency for most data points to be to the right of the vertical red line. This indicates that the majority of TCCOR were set "early" and the maximum sustained winds generally occurred later than predicted. This characteristic is mainly evident for the elevated TCCOR settings.

4. Contingency Table Analysis

A 3 x 3 contingency table was developed in an effort to determine the relationship of the wind speed probability values at each TCCOR to the observed maximum sustained winds (Table 6). Although it is understood that the wind speed probabilities, by definition, are not deterministic forecasts that can be "verified" by wind observations, the contingency table was used to simply categorize the TCCOR timelines based on consistent trends. Hits were assigned in cases where consistently low or high wind speed probability values (PCAT) were "matched" by the same category of observed winds (VCAT). In cases where the PCAT and VCAT were one category off a "MISS 1" was assigned, indicating a one category miss. A "MISS 2" was assigned when low wind speed probabilities were forecast at each TCCOR time but greater than 49-kt maximum sustained winds were observed. In cases where wind speed probabilities were consistently high at each TCCOR time but less than 34-kt winds were observed, a "FA" or "False Alarm" value was assigned. As an example, Table 7 contains several cases for each category. To be considered as an entry in each category, the probability category had to be constant for the progression of TCCOR settings.

Table 7.   The contingency table used to compare Wind Speed Probabilities to the observed maximum sustained winds.

Wind Speed Probability Category (PCAT)		Wind Verifying Category (VCAT)		
		1 (<34-kts)	2 (34 - 49-kts)	3 (>49-kts)
	1 (<34%)	HIT	MISS 1	MISS 2
	2 (34 - 66%)		HIT	MISS 1
	3 (>66%)	FA		HIT

Table 8.   Representative cases contained in the Hits, Miss1, Miss2 and FA categories. Each storm is identified by affected location (K = Kadena, S = Sasebo), year, and storm number. Two columns are defined for each TCCOR setting. The left column defines the actual wind probability and the right column defines the wind probability category.

	STORM	TCCOR III P	PCAT	TCCOR II P	PCAT	TCCOR I P	PCAT	MSW	VCAT
HIT	K 03 11W	67.5	3	67.5	3	83.7	3	62	3
HIT	K 06 08W	10.8	1	0.7	1	0.3	1	22	1
MISS 1	K 04 22W	0.8	1	2.1	1	22.8	1	48	2
MISS 2	K 07 04W	32.4	1	27.8	1	23.7	1	61	3
FA	S 05 14W	69.14	3	75.76	3	77.09	3	31	1

5. Wind Speed Probability Comparison

Each of the 42 TCCOR timelines were categorized as Hits, Misses and False Alarms. The averages of the 12-, 24- and 48-hour wind speed probabilities, calculated from the actual time of maximum sustained wind, were then compared. A T-test at a 95% confidence level was performed (Table 8) to determine if the probability category associated with storms characterized as Hits were significantly different from categories associated with storms in each of the other categories.

Table 9.   The results of the T-test performed to determine the differences in probability category between Hits, Misses and False Alarms. Values above the .05 alpha are shaded.

	P 48hrs	P 24 hrs	P 12hrs
MISS 1 Mean	0.1300	0.0046	0.0001
MISS 2 Mean	0.0600	0.0011	0.0000
FA Mean	0.3100	0.2700	0.0097

The results from the test indicate that at 48 hours, the properties of the Hits population are not significantly different from Misses or False Alarms, and thus, indistinguishable at a 95% confidence level. Additionally, there appears to be no significant difference between Hits and False Alarms at the 24-hour interval.

The significance of the uncertainty between Hits and False Alarms is of particular importance to TCCOR authorities because this represents an area where potential savings could be made. If False Alarms can be avoided, the costs associated with unnecessary TCCOR preparations in terms of time, operational readiness, and money could also be prevented. Lastly, False Alarms tend to reduce customer confidence in TCCOR forecasts. Without this trust and confidence the local populace may take the TCCOR less seriously, potentially resulting in more damage and even loss of life when the next storm strikes. Finally, at the level of TCCOR I, which is when destructive winds are most imminent, there are significant differences between Hits, Misses and False Alarms.

V. CONCLUSIONS AND RECOMMENDATIONS

A. THE TPU AND WIND SPEED PROBABILITY MODEL

In the process of studying the current TCCOR process, the use of the TPU and its overall validity became a focal point of this thesis. Though originally suggested as a way of recreating historical TCCOR timelines, it was instead investigated as an objective means of improving TCCOR forecasts. An in depth comparison between historical timelines and TPU predictions was performed in 42 cases where TCCOR were set between 2002 and 2007 at four fleet concentration areas in the WESTPAC. Differences between the historical and predicted timelines were analyzed for any significant trends or possible biases.

The Wind Speed Probability model, available at NRL, Monterey, also became a focal point of the study as both an objective and probabilistic means of comparing the timelines. It was useful in categorizing each TCCOR case based on comparisons with observed maximum sustained winds. The model was a very useful means of identifying consistent probability trends between a large number of different timelines as well as identifying trends between TCCOR III – I.

Statistical methods were then applied to determine if the parameters of the categorized cases were significantly different when compared to one another. In other words, were the Hits, Misses and False Alarm cases really distinguishable from one another based on the averaged wind speed probabilities at time intervals from the wind observations?

1. The TPU

From the scatter plots produced using Δt and $\Delta duration$, a positive relationship was identified between how much earlier the TPU was set and how much longer the subsequent predicted TCCOR durations lasted compared to the historical timelines. Additionally, it was obvious that in most cases the TPU predicted TCCOR earlier than they were set in reality. These variations introduce uncertainty into the validity of using

the TPU for anything other than "first guess" guidance for the forecaster. This uncertainty most likely represents the uncertainty in the official forecast used to define the TPU boundaries. A larger number of cases would need to be generated to determine if the positive relationship in the plots is due to a compensating effect as the TCCOR elevate and to identify a definite relationship between JTWC forecast accuracy and the TPU guidance. The TPU is initiated with official warning information and, is thus subject to the same error and subjectivity present in every official forecast.

2. The Wind Speed Probability Model

By plotting the wind speed probability categories (PCAT) vs. TCCOR III – I, clear trends were evident at low and high probabilities. Fewer cases of elevated TCCOR occurred when the probabilities were in the lower tercile, indicating a potential relationship between the wind speed probability model output and the likelihood of setting TCCOR II or TCCOR I. When probabilities were consistently in the upper tercile range, the frequency of elevated TCCOR steadily increased. In order for a probabilistic TCCOR threshold to be identified, however, a far greater number of cases would again need to be studied. It would also be useful to compare the results to the actual observed winds in each case to determine verification.

When using the wind speed probability and wind verification categories to classify storms as Hits, Misses and False Alarms, statistical differences between Hits and the other data sets were not present beyond the 24-hour (TCCOR II) interval. Between Hits and False Alarms, the data sets were not statistically different beyond the 12-hour interval (TCCOR I). TO distinguish between Hits and False Alarms, a more detailed study would be required to identify factors that distinguish between the two classifications. Additionally, a larger sample of storms might be necessary to identify factors that discriminate between the two categories.

B. FINAL COMMENTS AND FUTURE WORK

The greatest challenge of this thesis was obtaining a significant number of accurate, historical TCCOR timelines. Though 42 partial to complete timelines

ultimately comprised the data set, a far greater number could probably be created if the archives of log books at each of the four installations could be accessed. Although this would provide a larger historical population of timelines, there are other factors in the TCCOR process make it difficult to categorize by strictly objective measures.

The verbiage used in the official definitions of each TCCOR, such as "anticipated" and "possible," allows for a variety of interpretations and provides a degree of lee-way for the base commander or TCCOR authority to set the conditions as he or she deems appropriate. In the end, the TCCOR system is designed to ensure public safety and prevent damage from tropical cyclones. There will always be some subjectivity introduced at the human level, where the decisions are ultimately made, including local or operational circumstances that have nothing to do with meteorological forecasts. Future work has been proposed by Jim Hansen of NRL Monterey and others, however, that could eventually incorporate probabilistic language into the TCCOR definitions based on cost-loss ratios determined, in part, by wind speed probabilities.

Lastly, factors such as the unique topography and different operational constraints (aircraft, ships, etc.) at each of the four sites used in this study were not taken into account when categorizing the respective TCCOR cases. By focusing on site-specific TCCOR timelines and comparisons with the TPU and wind speed probabilities, etc., an opportunity exists to identify objective guidance that would take into account the aforementioned differences between each location.

This study has been the first to gather statistics on the timing and duration of TCCOR at various DoD installations throughout the Western North Pacific. The important data with regard to the settings, MSW, and TMSW are not easily attainable under the current operational constraints. While an inordinate effort was required to obtain these data, it is hoped that they will provide a basis for further study of the probabilistic approach to setting TCCOR.

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