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# Accuracy of tropical cyclone induced winds using TYDET at Kadena AB

Fenlason, Joel W.

Monterey, California. Naval Postgraduate School

# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**ACCURACY OF TROPICAL CYCLONE INDUCED WINDS USING TYDET AT KADENA AB**

by

Joel W. Fenlason

March 2006

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| Thesis Advisor: | Patrick A. Harr |
| Second Reader: | Russell L. Elsberry |

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# ACCURACY OF TROPICAL CYCLONE INDUCED WINDS USING TYDET AT KADENA AB


Joel W. Fenlason
Captain, United States Air Force
B.S., University of Washington, 1996


Submitted in partial fulfillment of the
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**March 2006**

Author: Joel W. Fenlason

Approved by: Patrick A. Harr
Thesis Advisor

Russell L. Elsberry
Second Reader

Philip Durkee
Chairman, Department of Meteorology

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When a tropical cyclone (TC) is within 360 nautical miles of Kadena AB, the Air Force's Typhoon Determination (TYDET) program is used to estimate TC-induced winds expected at the base. Best-track data and Joint Typhoon Warning Center (JTWC) forecasts are used to evaluate systematic errors in TYDET. The largest contributors to errors in TYDET are a systematic error by which wind speeds are too large and the lack of size and symmetry parameters. To examine these parameters, best-track and forecasts are used to classify TCs as small or large and symmetric or asymmetric. A linear regression technique is then used to adjust TYDET forecasts based on the best-track and forecast position, size, and symmetry categories. Using independent data, over 65 percent of the overall cross-wind forecasts were improved and more than 60 percent of the cross-wind forecasts were improved when verifying conditions noted a cross-wind of 20 knots or greater. The effectiveness of the corrections and implications for TYDET forecasts are examined in relation to errors in forecast data used to initialize TYDET. A similar approach as developed here for the TYDET model at Kadena AB is proposed for other bases within the Pacific theater.

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# I. INTRODUCTION

## A. OBJECTIVE

Over the years, many studies have been made for producing a climatologically-based tropical cyclone (TC) wind prediction tool for Kadena Air Base on Okinawa, Japan. These studies have resulted in a product that is referred to as TYDET (USAF Air Weather Service 1st Weather Wing 1980). Over many years of use, TYDET has provided useful forecasts of TC-induced winds at Kadena. However, there are noticeable errors in TYDET forecasts that have been related to various factors, which include the limited sample (20 years) of observations used to define the model, and difficulties associated with forecasting TC intensity that is a key input to the TYDET. Many of the inadequacies in TYDET have been thought to be associated with limitations in technology and resources at the time that it was created. Given recent improvements in observing, forecasting, and understanding of TC characteristics, it is believed that the accuracy of TYDET can be improved greatly.

The Department of Defense (DoD) has acknowledged a need for a program like TYDET at all air bases in tropical cyclone-prone regions. Before the task of creating programs for other bases can be accomplished, it is necessary to update and ensure the current (or replacement) product at Kadena AB is as accurate as possible. Therefore, a primary goal of this study is to examine the TYDET program to document errors in a systematic manner. Once systematic errors are identified, they may be addressed to improve forecasts of tropical cyclone-induced winds at Kadena.

The TYDET program is a necessary tool for bases in the Pacific region, and especially at Kadena, due to the large number of TCs that form yearly in the western North Pacific Ocean. On average, Kadena is directly affected by 3-4 storms per year and indirectly by numerous more storms. During 2000-2005, Kadena AB utilized the current version of TYDET at least 50 times, which averages to be over eight TCs per year. From 1945-2004, 100 TCs occurred in which winds of 50 knots or greater have been observed at Kadena AB, which averages to 1.67 TCs per year in which destructive winds are observed. Improvement of TYDET is imperative for the safety of resources and personnel at Kadena AB, and an improved TYDET will serve as a baseline for development of similar tools throughout the Pacific area of responsibility (AOR).

It is the purpose of this study to determine errors associated with the basic TYDET formulation and to isolate those that are tied to the accuracy of the TC forecast from the Joint Typhoon Warning Center (JTWC). If many of the inherent problems with TYDET can be eliminated, then as the JTWC forecast continues to improve, so will the wind forecasts generated by the TYDET program. In this study, it is hypothesized that major errors in TYDET are due to the lack of consideration of storm size and asymmetry. When TYDET was originally created (Climatology Branch HQ 1st Weather Wing 1972), these parameters were not routinely analyzed. This study will attempt to increase the accuracy of the TYDET forecast by updating the forecast tool to take into account errors tied to size, asymmetry, location, and approach direction of TCs affecting Kadena.

## B. BACKGROUND

Kadena AB, Japan is on the island of Okinawa about 900 miles south-southwest of Tokyo, Japan. It is known as the “Keystone of the Pacific” because it is located strategically in the western North Pacific such that it is possible to rapidly deploy its more than 80 aircraft throughout the Asia-Pacific region. However, this strategic location comes at some cost as Kadena is in a prime TC path. Tropical cyclones threaten the base, aircraft, and personnel with damaging and life-threatening winds numerous times each year. Kadena’s location necessitates accurate and timely warnings of storms that threaten the base, as well as possible effects from these approaching storms.

The JTWC provides intensity and track forecasts for TCs in the western North Pacific, but they do not provide a point forecast for the base. This point forecast is produced by the 20th Operational Weather Squadron (OWS) at Yokota AB, Japan in collaboration with the combat weather team (CWT) at Kadena AB.

Both the OWS and Kadena CWT need to be able to take the JWTC intensity and track forecasts and tailor them to provide an accurate and timely forecast for the base.

This forecast is important in the evacuation of aircraft, as well as the timely preparations by base personnel and of other base resources. The base has over 6,000 military members and a population of 22,000 from five major commands as well as family members, U.S. civilians, Japanese workers, and contractors. The base has $6 billion in resources, including $4 billion in aircraft and equipment and capital assets valued at $2 billion (official Kadena AB homepage http://www.kadena.af.mil). These numbers illustrate the necessity for accurate forecasts. The time in which aircraft can be evacuated is limited by the onset of winds and the orientation of these winds to the runway, which may cause runway cross-winds that are above take-off thresholds. The timing of the onset of damaging winds is also important to those aircraft and people being sheltered, as the base must be prepared to withstand these winds. The OWS and CWT personnel use TYDET to aid them in the forecast and reduce the amount of time that personnel must spend analyzing the models.

The original TYDET program for Kadena AB, Japan was created in 1972 (Climatology Branch HQ 1st Weather Wing 1972) and has been updated in 1983 (CR 83-08 1983) and 1986 (official correspondence 1986). No significant improvements have been made since 1986, although the program has been converted from an out-dated computer code to an easily used Microsoft Excel program. The input screen and output from this Excel spreadsheet are depicted in Figures 1 and 2.

The TYDET model utilizes observed wind speeds and directions of Kadena AB relative to the corresponding storm location to estimate the wind speeds and directions that will be experienced from the current storm. The track and intensity forecast from the JTWC are input to the program and then the program returns local winds at Kadena AB for each hour out to 72 hours in terms of the direction, speed, gust speed, and extreme gust speed. It then uses these values along with the runway headings to calculate cross-winds based on the sustained wind speed and the gust wind speed.

**Data Input Screen for Kadena WDPN Bulletin**

**Enter data in the shaded cells only. For blank cells, enter "np" (no plot).**

| | | | | | | |
|---|---|---|---|---|---|---|
| **Storm Name:** | NARI | | | **Storm Number:** | 20W | |
| **Warning Number:** | 29 | | | | | |
| | **Date** dd mmm yy | **Time (Z)** 2 digits | **Latitude** | **Longitude** | **Sustained Wind** | **Gust** |
| **00 hr** | 13 Sep 01 | 00 | 26.5 | 126.5 | 75 | 90 |
| **12 hr** | 13 Sep 01 | 12 | 27.3 | 125.8 | 65 | 80 |
| **24 hr** | 14 Sep 01 | 00 | 27.5 | 125.2 | 70 | 85 |
| **36 hr** | 14 Sep 01 | 12 | 27.1 | 124.8 | 65 | 80 |
| **48 hr** | 15 Sep 01 | 00 | 26.4 | 124.3 | 65 | 80 |
| **72 hr** | 16 Sep 01 | 00 | 25.5 | 123.0 | 90 | 110 |

Figure 1. Input screen in the TYDET program that depicts storm information from JTWC pertaining to the forecast TC location and intensity.

The original TYDET program estimated the winds at Kadena AB based on nomograms of the observed conditions at Kadena AB when the storm was in a given sector. The nomogram was composed of a 16 compass-point (true versus magnetic) azimuthal nomogram centered on the station. The nomogram was then divided into six concentric rings at 60 nautical mile (n mi) intervals from Kadena out to 360 n mi (USAF Air Weather Service 1st Weather Wing 1980). Therefore, there are 96 sectors in which average wind values have been calculated from observations whenever storms were in these sectors. An earlier (Climatology Branch HQ 1st Weather Wing 1972) version only contained 71 sectors and is still used in conjunction with the updated nomogram for storms below 64 knots or typhoon strength. The updated nomogram with 96 sectors is the only nomogram used for storms above 64 knots or typhoon strength.

A total of six nomograms were used: sustained wind speed, sustained wind direction, gust speed, gust direction, extreme gust speed, and extreme gust direction. After the observed values at Kadena AB were obtained and its position with respect to the storm position were calculated, the observed values were then normalized by dividing by the tropical cyclone maximum wind speed and gust, respectively. These percentages were calculated for each best-track point in which the TC was within 360 n mi of Kadena AB, and then an average percentage for each sector was determined. Analyses of the percentage values for both the sustained wind and the gust values were made after smoothing each of the 96 sectors by averaging the initial value with those in the adjacent segments within the same distance ring (USAF Air Weather Service 1st Weather Wing 1980). Because the radial gradients were too large, the percentages were not smoothed radially.

| | Date | Time | Latitude | Longitude | Distance nm | Bearing | Storm Winds Sustained | Storm Winds Gusts | (A7) | (A8) | Nomogram Direction | Nomogram Sustained | Nomogram Gust | Nomogram Extreme Gust | Nomogram Sustained X-Wind | Nomogram Gust X-Wind |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 00 hr | 12 Sep 01 | 06 | 26.3 | 127.0 | 44 | 263 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 01 hr | 12 Sep 01 | 07 | 26.4 | 127.0 | 43 | 270 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 02 hr | 12 Sep 01 | 08 | 26.4 | 127.0 | 43 | 270 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 03 hr | 12 Sep 01 | 09 | 26.4 | 127.0 | 43 | 270 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 04 hr | 12 Sep 01 | 10 | 26.5 | 127.0 | 44 | 278 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 05 hr | 12 Sep 01 | 11 | 26.5 | 127.0 | 44 | 278 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 06 hr | 12 Sep 01 | 12 | 26.5 | 127.0 | 44 | 278 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 07 hr | 12 Sep 01 | 13 | 26.6 | 127.0 | 45 | 286 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 08 hr | 12 Sep 01 | 14 | 26.6 | 127.0 | 45 | 286 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 09 hr | 12 Sep 01 | 15 | 26.6 | 127.0 | 45 | 286 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 10 hr | 12 Sep 01 | 16 | 26.6 | 127.0 | 45 | 286 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 11 hr | 12 Sep 01 | 17 | 26.6 | 127.0 | 45 | 286 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 12 hr | 12 Sep 01 | 18 | 26.6 | 126.9 | 50 | 284 | 90 | 110 | 68 | 89 | 140 | 42 | 62 | 81 | 42 | 62 |
| 13 hr | 12 Sep 01 | 19 | 26.7 | 126.9 | 52 | 291 | 90 | 110 | 70 | 88 | 200 | 43 | 63 | 80 | 21 | 31 |
| 14 hr | 12 Sep 01 | 20 | 26.7 | 126.9 | 52 | 291 | 90 | 110 | 70 | 88 | 200 | 43 | 63 | 80 | 21 | 31 |
| 15 hr | 12 Sep 01 | 21 | 26.7 | 126.9 | 52 | 291 | 89 | 109 | 70 | 88 | 200 | 43 | 63 | 79 | 21 | 31 |
| 16 hr | 12 Sep 01 | 22 | 26.8 | 126.9 | 54 | 297 | 89 | 109 | 70 | 88 | 200 | 43 | 63 | 79 | 21 | 31 |
| 17 hr | 12 Sep 01 | 23 | 26.8 | 126.9 | 54 | 297 | 89 | 109 | 70 | 88 | 200 | 43 | 63 | 79 | 21 | 31 |
| 18 hr | 13 Sep 01 | 00 | 26.8 | 126.8 | 59 | 295 | 88 | 108 | 70 | 88 | 200 | 42 | 62 | 78 | 21 | 31 |
| 19 hr | 13 Sep 01 | 01 | 26.9 | 126.8 | 62 | 300 | 88 | 108 | 70 | 88 | 200 | 42 | 62 | 78 | 21 | 31 |
| 20 hr | 13 Sep 01 | 02 | 26.9 | 126.8 | 62 | 300 | 88 | 108 | 70 | 88 | 200 | 42 | 62 | 78 | 21 | 31 |

Figure 2. Sample output from the Microsoft Excel-based TYDET program. The A7 and A8 columns contain the percentage of the overall TC wind speed and wind gust that climatologically will be observed at Kadena AB. All of the nomogram fields describe calculations based on the original nomograms. The shaded fields are data that are entered by the user at the 0-, 12-, 24-, 36-, 48-, and 72-hour forecast times.

The isolines on the final nomograms represent analyses of the smoothed data, in which some minor smoothing of anomalous curvature in the isolines was unavoidably subjective (USAF Air Weather Service 1st Weather Wing 1980). The nomograms for all of the variables were smoothed in the same way. On the nomogram (Figure 3), three percentage values are included in each sector: (i) mean sustained wind speeds; (ii) maximum wind speeds; and (iii) total number of cases in which a storm was located in that sector. Note that in Figure 3 the total number of times a storm has been in any given sector is quite small for many of the sectors nearest to Kadena. The smoothed isolines depicted in Figure 4 were derived from the corresponding original nomogram in Figure 3. It is interesting that the intensity isolines/ratios in Figure 4 are not symmetric about the Kadena position. Storms that are to the northwest of Kadena will have fewer terrain effects and therefore the effects of the storm will be felt at greater distance than when the storm is to the east of Okinawa. The isolines also extend more to the southwest compared to the southeast, because the strongest winds are typically to the right of the tropical cyclone as it tracks past Okinawa. The directional nomogram (Figure 5) has a large bow in the southwest direction in the 140 degree contour that may possibly be due to local terrain effects and typical tropical cyclone tracks past Okinawa.

The TYDET program utilizes these nomograms through various tables (Figure 6). The tables are formatted with the center value (100) depicting the percentage of the storm winds expected when the storm is directly overhead. The percentages then extend out radially at 60 mile intervals. Essentially, the new tables break the nomograms into 121 sectors, but some of these sectors have duplicate values since the table is based on the original 96 sectors. The program then accesses these data through formula that are dependent upon storm intensity and location. Values are then calculated and variables are determined to give forecasters guidance as to the wind conditions to expect at Kadena AB, Okinawa.

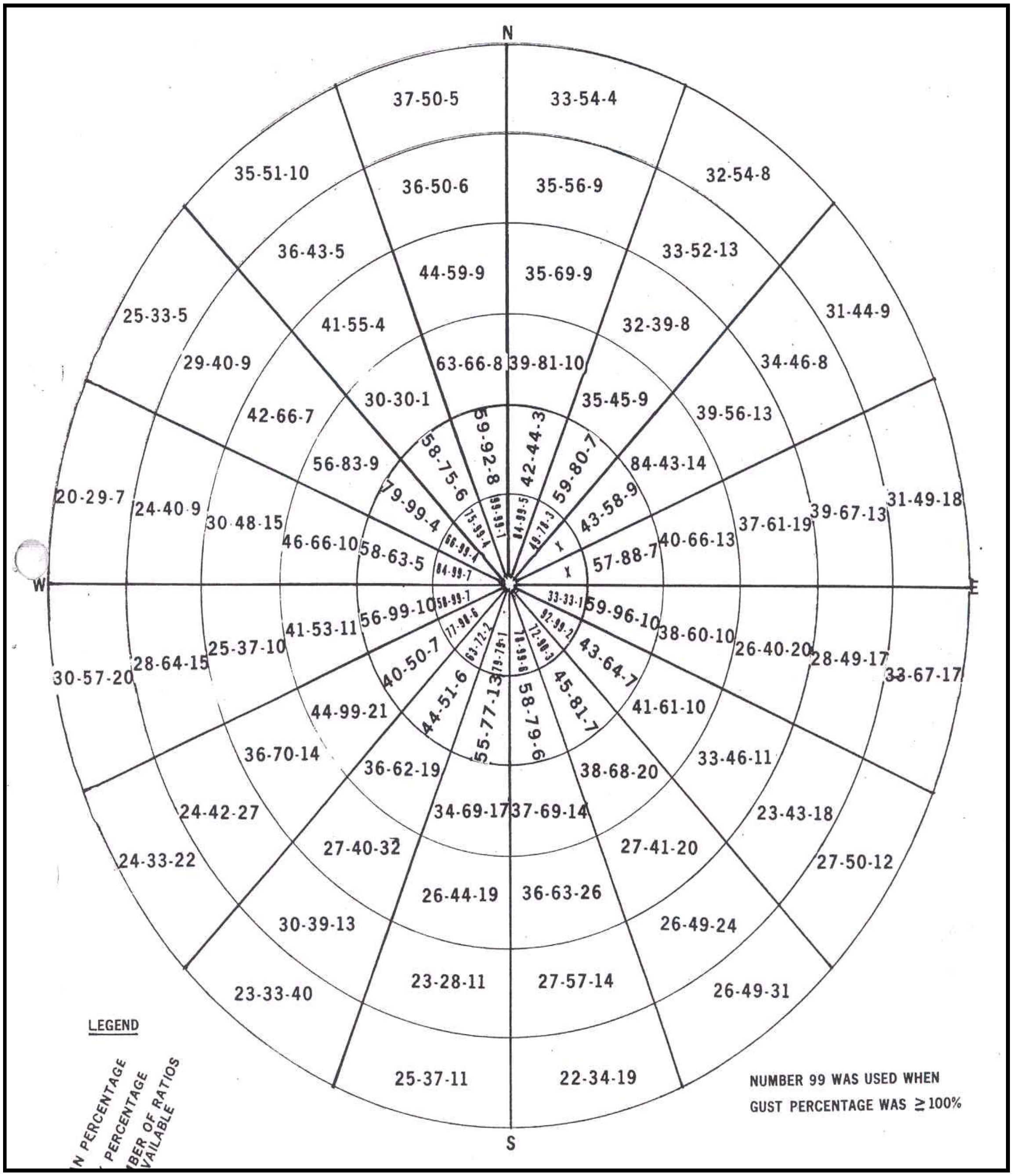


Figure 3. The first number in each sector is the mean sustained wind percentage (i.e., the wind at Kadena AB is this percent of the maximum sustained surface winds when the storm is located in this sector), the second number is the maximum (including gusts) wind percentage, and the third number is the number of storms/observations from that sector. Isolines in Figure 4 were analyzed to allow interpolation of values from this chart. The later Excel program tables were also derived from this chart.

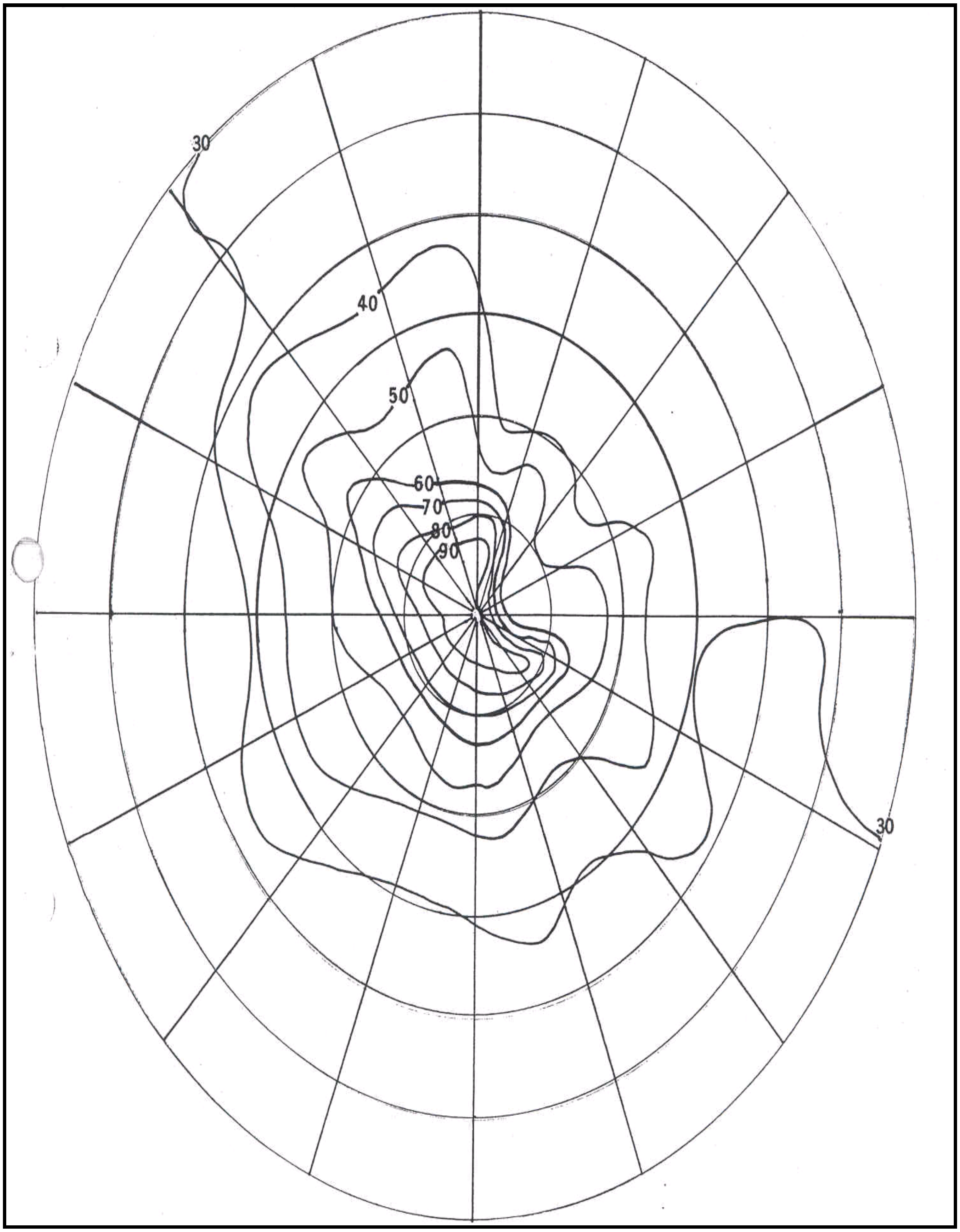


Figure 4. Sustained wind (percentage of tropical cyclone maximum sustained wind) expected at Kadena AB when the tropical cyclone is located in one of the 96 segments of the TYDET grid.

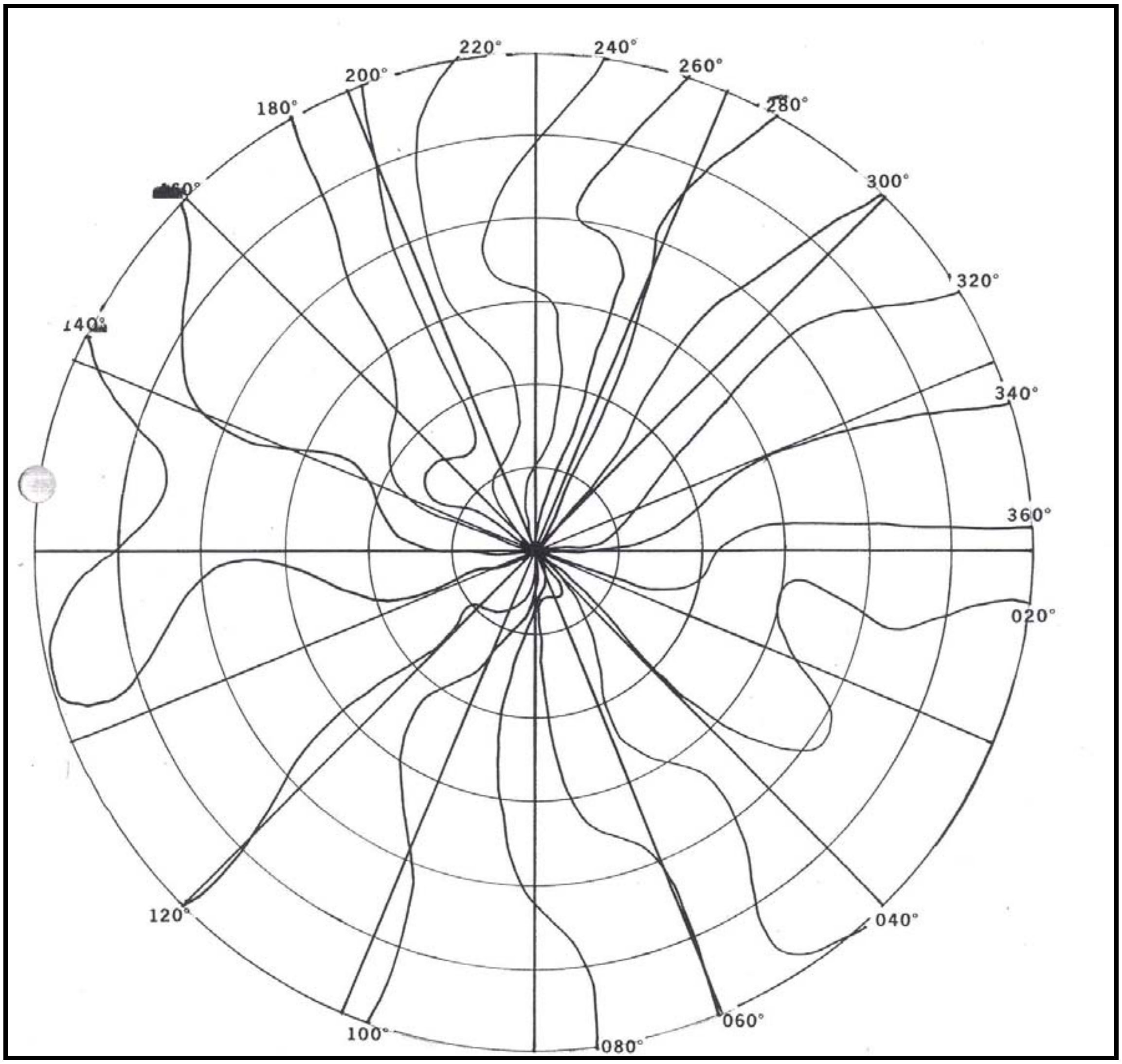


Figure 5. Isolines depicting the wind direction expected at Kadena AB when the tropical cyclone is located in one of the 96 segments.

| GR_One | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 22 | 23 | 25 | 27 | 27 | 28 | 28 | 28 | 27 | 26 | 24 |
| 2 | 23 | 25 | 27 | 29 | 31 | 32 | 32 | 32 | 31 | 28 | 26 |
| 3 | 25 | 27 | 30 | 36 | 39 | 40 | 39 | 37 | 34 | 31 | 28 |
| 4 | 25 | 29 | 36 | 43 | 50 | 49 | 43 | 40 | 36 | 32 | 29 |
| 5 | 26 | 31 | 39 | 52 | 66 | 61 | 50 | 43 | 37 | 33 | 28 |
| 6 | 27 | 32 | 40 | 50 | 68 | 100 | 55 | 45 | 36 | 30 | 27 |
| 7 | 26 | 30 | 36 | 45 | 56 | 66 | 50 | 40 | 33 | 29 | 27 |
| 8 | 25 | 27 | 32 | 38 | 41 | 43 | 39 | 34 | 30 | 27 | 25 |
| 9 | 23 | 25 | 28 | 30 | 32 | 32 | 31 | 28 | 27 | 25 | 23 |
| 10 | 20 | 23 | 25 | 27 | 27 | 27 | 26 | 25 | 23 | 22 | 20 |
| 11 | 17 | 20 | 23 | 23 | 24 | 24 | 23 | 22 | 21 | 20 | 17 |

Figure 6. Sample table from the Excel-based TYDET program depicting how the original nomograms were incorporated. The far left column is a placeholder to aid the program when it calls the values. The other columns contain the percentage of the maximum sustained surface wind that Kadena AB should observe when the storm is located in a given grid point.

## C. PROPOSED IMPROVEMENTS

When the TYDET program was developed, storm size was not taken into consideration. Because of differences in storm size and different radial distributions of winds in each individual storm, it is hypothesized that the absence of considering these factors is the primary limiting factor in the current version of TYDET. An additional limitation is that TYDET does not account for storm asymmetries due to different directions of approach to Kadena, which can lead to large errors in wind speed and direction at Okinawa. Since the nomogram percentages are averages of storms with a variety of sizes, the medium- or average-size storms will be expected to result in the most accurate Kadena wind forecasts. Applying TYDET to symmetric storms will also be expected to return the most accurate forecasts.

Another limitation of the TYDET program is the small database of storms in the development sample. Many of the 96 sectors in Figure 3 have only one observation available. No sector has more than 46 observations and the average is only 17 per sector. However, this average is deceiving because the number of observations falls off considerably toward the inner rings when the storm is closer to Kadena AB. No more than eight observations are available within the inner ring, with an average of only four observations, which leads to misrepresentation of the winds and directions when the storm is close to or over Kadena AB. Obviously, a larger sample would improve the accuracy of the nomograms of wind speeds and directions for storms that pass, or are forecast to pass, close to Kadena AB.

This small sample size was due to the relatively small number of years (28 years within 1949-1968 and 1973-1981) utilized in the derivation of the TYDET program, and those years had relatively fewer storms that affected Kadena AB than in recent years. Thus 25 additional seasons since 1981 might be added, which would more than double the sample size. Many of the sparsely covered segments could be filled with the additional 25 years of data, and thus improve the TYDET program predictions. However, inclusion of size and symmetry effects is only possible over a limited period of since size and symmetry data have only been included in best-track data since 2001. Therefore, only a limited sample size will be available to include these parameters.

Adding observations to the database may not be enough to correct some of the inherent errors in TYDET. It may be necessary to make other corrections to the program based on some of the consistent errors that are discovered during the course of this study. For example, it may be possible to account for some asymmetries arising from different storm approach directions and different storm structures. Such corrections may also make the program have a more dynamical structure. It is hypothesized that including corrections for storm size and asymmetry will improve the TYDET program more than increasing the sample size.

The TYDET program has many upsides and some correctable downsides. Given that no forecasting model or tool is perfect, the existing TYDET program is worth improving and then applying lessons learned and methodologies to create similar models for all bases in the Pacific theater that are threatened by TCs.

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# II. METHODOLOGY

## A. DATA

The data used for testing the TYDET program were from the JTWC best-track files and forecasts for the years 2001-2004. For 2005, the real-time data sets were used. The best-track data and the JTWC forecasts were used to apply the TYDET program for each time that both the best-track position and forecast positions were within 360 nautical miles of Kadena AB.

For the application of TYDET using best-track data, the TC maximum wind speeds were taken directly from the best-track values. If wind gusts were not recorded in the best-track data, then the wind gusts were derived by applying the JTWC-standard 125 percent of the sustained wind and rounding to the nearest multiple of five. The maximum wind speeds and gusts for the JTWC forecasts were taken directly from the text forecast. The wind radii, storm latitude/longitude, and forecast times were taken directly from the best-track data and JTWC text forecasts. The 34-knot wind radii from the best-track data and JTWC text forecasts were used to compute the size and an asymmetric proxy for the storm. The use of the 34-knot wind radii was one reason the data were limited to 2001 and later, since the best-track data did not include 34-knot wind radii prior to 2001. The observations for Kadena, AB archived at the Air Force Combat Climatology Center (AFCCC) in Ashville, NC were used as the verifying data.

## B. EVALUATING THE TYDET PROGRAM

The best-track data that were input to the TYDET program were assumed to be perfect data. Therefore, any differences between the TYDET output values and the observed values were attributed to errors or biases in the TYDET program. The JTWC official 0-, 12-, 24-, 36-, 48-, and 72-hour forecasts were used to compare the TYDET biases due to systematic errors in the model and the biases or errors due to JTWC forecast data. The TYDET program outputs the forecast values for wind speed, wind gust, direction of wind, extreme gust, and the cross-wind at Kadena AB. Two modes of operation were utilized. That is, the TYDET was executed using the best-track position and intensity values for comparison with the real-time application using the JTWC forecast values. The difference in errors indicates the proportion due to incorrect JTWC forecast values versus errors inherent to the TYDET approach.

To determine the forecast parameters, a series of "if then" statements are executed to determine a grid box for the location of the storm based on the input latitude and longitude. That is, the area around Kadena, AB was divided into an 11 by 11-outer grid (Figure 7) with each grid box having dimensions of one-degree latitude by one-degree longitude. The outer boundaries are 20.90N to 31.90N and 122.30E to 133.30E with Kadena AB located in the center at 26.35N and 127.77E. A few grid boxes that fell outside of the 360 n mi radius were not given grid numbers. To account for the most important and subtle changes closer to Okinawa, an inner seven by seven grid was defined from 24.90N to 27.90N and 125.80E to 129.80E (Figure 8). This inner grid has 0.5-degree latitude by 0.5-degree longitude grid boxes. Each grid box was assigned an M coordinate and an N coordinate. These M and N coordinates were used to decide in which grid box the storm was located.

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 31.9N | M0,N10 | M0,N9 | M0,N8 | M0,N7 | M0,N6 | M0,N5 | M0,N4 | M0,N3 | M0,N2 | M0,N1 | M0,N0 |
| | M1,N10 | M1,N9 | M1,N8 | M1,N7 | M1,N6 | M1,N5 | M1,N4 | M1,N3 | M1,N2 | M1,N1 | M1,N0 |
| | M2,N10 | M2,N9 | M2,N8 | M2,N7 | M2,N6 | M2,N5 | M2,N4 | M2,N3 | M2,N2 | M2,N1 | M2.N0 |
| | M3,N10 | M3,N9 | M3,N8 | M3,N7 | M3,N6 | M3,N5 | M3,N4 | M3,N3 | M3,N2 | M3,N1 | M3,N0 |
| | M4,N10 | M4,N9 | M4,N8 | M4,N7 | M4,N6 | M4,N5 | M4,N4 | M4,N3 | M4,N2 | M4,N1 | M4,N0 |
| | M5,N10 | M5,N9 | M5,N8 | M5,N7 | M5,N6 | M5,N5 | M5,N4 | M5,N3 | M5,N2 | M5,N1 | M5,N0 |
| | M6,N10 | M6,N9 | M6,N8 | M6,N7 | M6,N6 | M6,N5 | M6,N4 | M6,N3 | M6,N2 | M6,N1 | M6,N0 |
| | N/A | M7,N9 | M7,N8 | M7,N7 | M7,N6 | M7,N5 | M7,N4 | M7,N3 | M7,N2 | M7,N1 | N/A |
| | N/A | M8,N9 | M8,N8 | M8,N7 | M8,N6 | M8,N5 | M8,N4 | M8,N3 | M8,N2 | M8,N1 | N/A |
| | N/A | M9,N9 | M9,N8 | M9,N7 | M9,N6 | M9,N5 | M9,N4 | M9,N3 | M9,N2 | M9,N1 | N/A |
| 20.9 N | N/A | M10,N9 | M10,N8 | M10,N7 | M10,N6 | M10,N5 | M10,N4 | M10,N3 | M10,N2 | M10,N1 | N/A |
| | 122.3E | | | | | | | | | | 133.3E |

Figure 7. Grid boxes used for the outer grid areas. Each grid box represents a sector that is located within 360 n mi of Kadena AB in the Microsoft Excel version of TYDET. Kadena, AB is located in the center grid box (M5,N5).

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 27.9N | M0,N8 | M0,N7 | M0,N6 | M0,N5 | M0,N4 | M0,N3 | M0,N2 | M0,N1 | M0,N0 |
| | M1,N8 | M1,N7 | M1,N6 | M1,N5 | M1,N4 | M1,N3 | M1,N2 | M1,N1 | M1,N0 |
| | M2,N8 | M2,N7 | M2,N6 | M2,N5 | M2,N4 | M2,N3 | M2,N2 | M2,N1 | M2.N0 |
| | M3,N8 | M3,N7 | M3,N6 | M3,N5 | M3,N4 | M3,N3 | M3,N2 | M3,N1 | M3,N0 |
| | M4,N8 | M4,N7 | M4,N6 | M4,N5 | M4,N4 | M4,N3 | M4,N2 | M4,N1 | M4,N0 |
| | M5,N8 | M5,N7 | M5,N6 | M5,N5 | M5,N4 | M5,N3 | M5,N2 | M5,N1 | M5,N0 |
| 24.9N | M6,N8 | M6,N7 | M6,N6 | M6,N5 | M6,N4 | M6,N3 | M6,N2 | M6,N1 | M6,N0 |
| | 125.8E | | | | | | | | 129.8E |

Figure 8. Grid boxes used for the inner grid areas. Each grid box represents a sector that is located within 360 n mi of Kadena AB in the Microsoft Excel version of TYDET. Kadena, AB is located in the center grid box (M3,N4).

The TYDET program then called the value from the appropriate grid box depending upon whether it was calculating the wind speed, wind gust or the wind direction. As discussed earlier, the values in the grid boxes were incorporated from the nomograms in the original TYDET program, which represent a percentage of the sustained wind speed of the storm. The gust that should be present at Kadena, AB is obtained by multiplying it by the storm maximum gust and then multiplying by 0.01 to convert from a percentage to the actual wind gust forecast. The sustained wind speed at Kadena, AB was calculated using this gust value and multiplying it by 0.67, since the TYDET calculations assume that the wind speed is 67 percent of the wind gust. A list of each calculation and the associated tables that they call can be found in Appendices A and B, respectively.

The forecast value minus the observed value at Kadena AB for the given time defines the error. A positive speed difference represents an over-forecast by the TYDET program (i.e., 17 would mean that the forecast value was 17 knots higher than the observed value). The cross-wind forecast error is defined to be in knots. A positive (clockwise) wind direction error represents an over-forecast. For example, if the wind is forecast to be 120 degrees and the observed wind is 90 degrees, the over-forecast angle is 30 degrees. To avoid direction error values over 180 degrees, the process of converting values to their reciprocal sign was used. For example, if the observed value was 10 degrees and the forecast value was 330 degrees, then instead of having a 320 degree error the error was defined to be -40 degrees. This better convention represented the direction error and kept the large errors from dominating the statistics.

The direction error was also calculated with respect to the Kadena AB runway heading, since the ultimate goal of the TYDET study is to improve cross-wind forecasts. This proved to be a difficult way to define direction error as well, since a 180-degree directional difference would now be represented as a 0-degree error due to an equivalent cross-wind component. It was determined that the best way to represent both speed and direction would be to convert to u- and v-components and then convert back to speed and direction after calculations were made. This approach allowed a better representation of the direction and an equivalent representation of the speed.

The TYDET program returns forecast wind conditions for Kadena AB anytime the location of the storm is within a 360 nautical mile radius. For this evaluation, the observed conditions are used to evaluate all six forecast periods (0, 12, 24, 36, 48, and 72 hours). For example, the observed conditions on 17 September 2002 would be used to validate the 48-hour forecast from 15 September 2002 and the 72-hour forecast from 14 September 2002. There were only a few times when comparing TYDET forecast values and an observed value was not possible while the storm was within 360 nautical miles. One large set of missing observations occurred during Typhoon Songda when all observations for 6 September 2004 were missing.

Storm quadrants were defined with respect to the movement of the storm since the winds to the right of the path are generally higher than to the left. Thus, the heading of the storm was defined along the y-axis and the right-front quadrant will always be in the upper right of the grid and the right-rear quadrant will always be in the lower right corner of the grid as the storm moves. The evaluation of the different errors based on storm quadrant affecting Kadena AB helped to factor in storm approach direction toward Kadena AB. Whereas this definition differs from the geographically-oriented JTWC definition of quadrants (northwest, northeast, southeast, and southwest), it provides a more physically-based assessment of impacts due to size and asymmetry. All references to right, left, front, and rear will refer to the quadrants with relation to storm movement, and references to northwest (NW), southwest (SW), northeast (NE), and southeast (SE) will refer to JTWC-type quadrants.

The wind radii from the best-track data were used to determine the size and symmetry of the storms. The four JTWC quadrants (NW, SW, NE, and SE) of 34-knot wind radii were averaged to determine the overall size of the storm. The storm sizes with values in the bottom $50^{th}$ percentile were classified as small storms and those in the top $50^{th}$ percentile were classified as large storms. It was therefore possible that a single storm could be both large and small during its lifetime. The critical value that distinguished between a small and large storm was a summed value of 580 n mi or an average of 145 n mi per quadrant.

To characterize the asymmetry of the storms, the differences between the smallest 34-knot wind radii and the largest 34-knot wind radii were calculated. Those storms in the top $50^{th}$ percentile were classified as asymmetric and those in the bottom $50^{th}$ percentile were classified as symmetric. The critical value for this asymmetry parameter that separates an asymmetric and a symmetric storm was 30 nautical miles.

### C. CLASSIFICATION AND ANALYSIS TECHNIQUE

A total of 22 storms were analyzed in this study. The criterion for inclusion in the sample was that the storm passed within 360 n mi of Kadena AB at some time in its life cycle (Figure 9). This sample included all of the defined classifications of storms. That is, six small-symmetric, three small-asymmetric, six large-symmetric and seven large-asymmetric storms were included in this sample (Figure 10).

The speed and direction errors for each classification of storm were plotted on a map to produce contour charts of speed, direction and cross-wind errors with respect to Kadena AB. These error patterns were used to establish factors associated with errors in TYDET forecasts and thus establish where corrections to the TYDET program are needed. Due to the complexity of defining a directional error and what constitutes a positive or negative directional error, the u- and v-components and the corresponding u- and v-component errors of the storm were also calculated. The TYDET forecast u- and v-component errors were also calculated by subtracting the observed u and v error values.

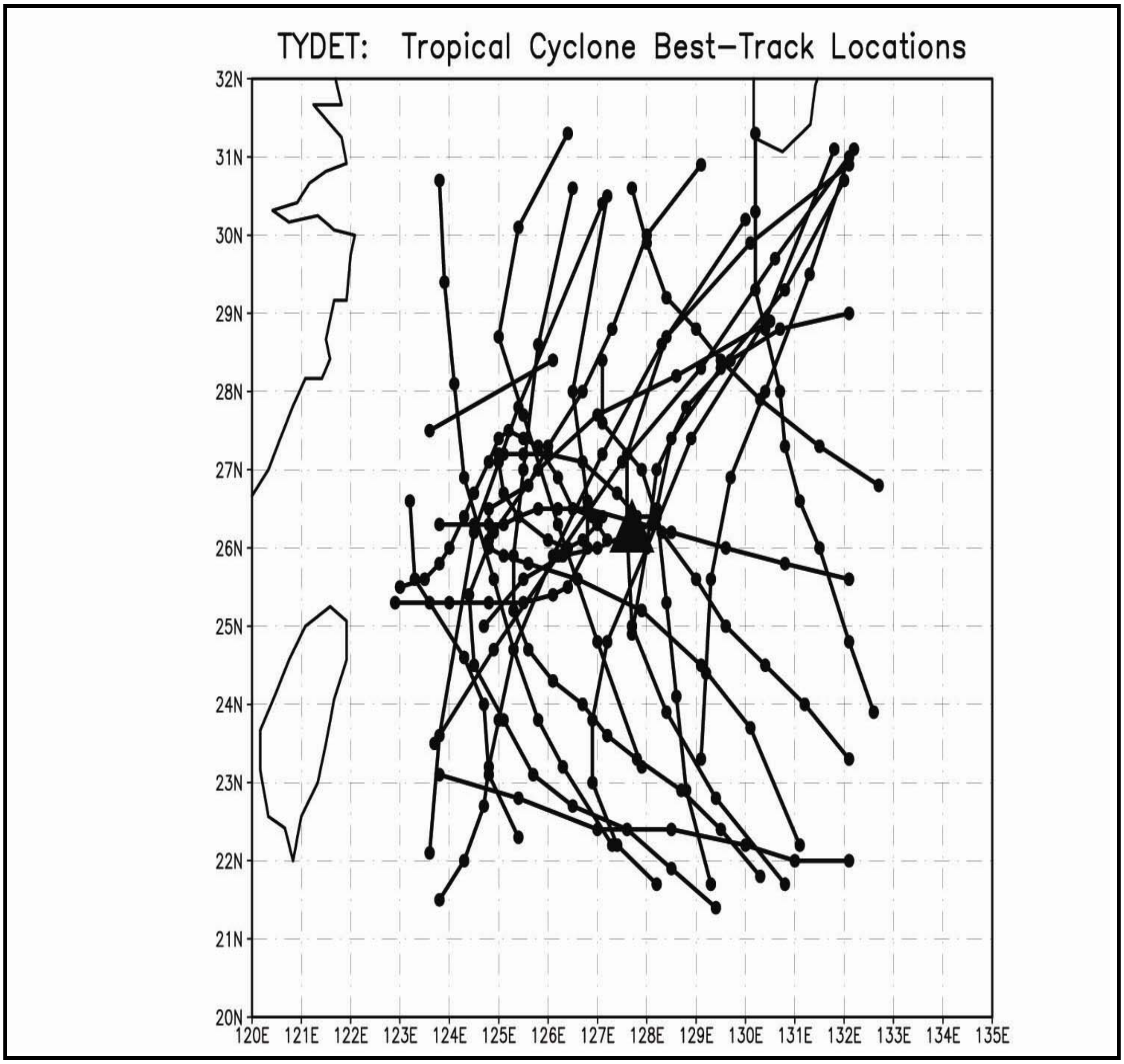


Figure 9. Best-track positions (dots at 6-h intervals) of 22 storms that approached within 360 n mi of Kadena AB between 2001 and 2005.

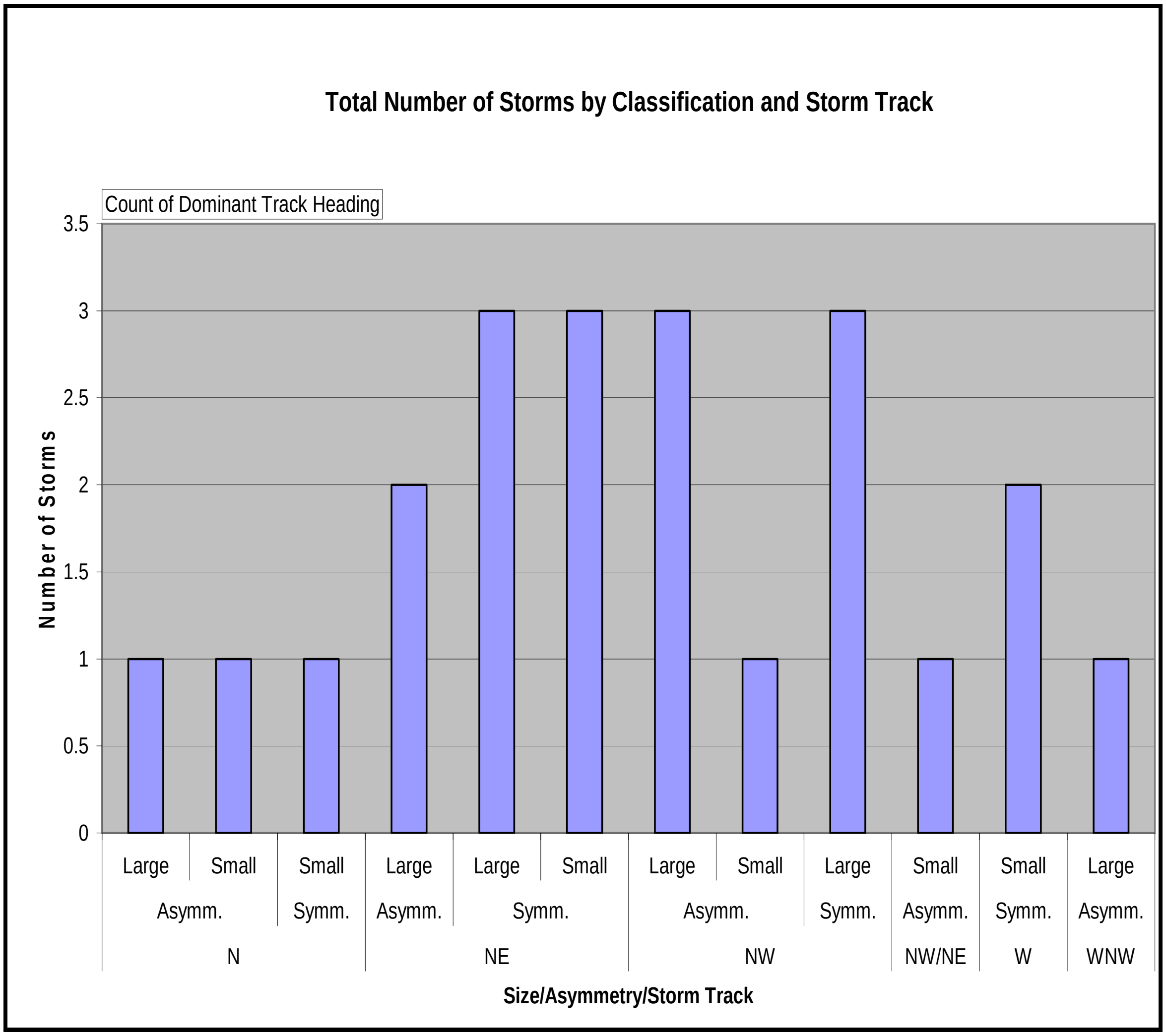


Figure 10. Numbers of storms characterized by storm size, asymmetry, and storm track. The labels along the x-axis are direction of approach, symmetry, and size.

## D. STATISTICAL ADJUSTMENTS TO TYDET

Because the availability of best-track size and asymmetry data are limited to a five-year period, it is not feasible to re-derive the entire TYDET nomogram system. Therefore, it was decided to assess errors that may be due to TC size and symmetry for the purpose of making statistical-based adjustments to the original TYDET forecast based on this relationship between error and TC characteristics.

To determine the adjustments to be made to each wind variable in the TYDET program, a series of linear regressions were made with the predictand defined as the TYDET wind speed error for each forecast interval. Various predictors have been evaluated to provide this regression estimate of the expected TYDET error that could then be used to adjust the TYDET forecast output. Because of the hypothesis that the primary error sources to TYDET are the absence of storm size and asymmetry inputs, these two variables are included in the regression predictor set along with other input parameters used in TYDET, which include storm latitude, longitude, and maximum wind speed. The regression also incorporated TYDET-calculated values such as the forecast wind speed at Kadena AB.

A stepwise linear regression model was used to assess the significance of each potential predictor of TYDET error. To enter the model, the significance of a potential predictor had to exceed a p-value of 0.15. The metric for success is that the overall root-mean-square-error (RMSE) of the adjusted TYDET program is smaller than the RMSE of the un-adjusted TYDET forecasts.

Finally, a jackknife procedure was used to estimate the likely reliability of the corrections for independent data sets. This procedure simulated the different forecasts that would be associated with additional storms affecting Kadena AB. That is, the RMSE from the jackknife procedure should be smaller than for the un-adjusted TYDET if the regression procedure is to improve the performance of TYDET with independent data sets.

The regression technique was used to create adjusted TYDET speed and u- and v-component forecasts. Then, the updated speed and direction values were used in TYDET calculations to compute the cross-wind. These values were then compared with both the observed values and original TYDET forecast values to determine an average improvement. Separate calculations were made using the best-track values of position and maximum winds and the JTWC forecasts for these inputs to TYDET. The linear regression technique was used to calculate the adjustments for storms in which the right-front and right-rear quadrants affected Kadena AB.  Storms in which the left-front and left-rear quadrants affected Kadena AB were too few in number to develop regressions for corrected wind speeds.  The limited number of data points led to large error values dominating the smaller error values, which did not allow a robust adjustment for the errors in these quadrants.

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# III. ANALYSIS OF TYDET

## A. PERFORMANCE USING BEST-TRACK DATA

The input of JTWC best-track data to the TYDET model is equivalent to providing perfect forecast information. The assumption is that input of perfect information will provide a forecast that will isolate the systematic errors associated with the formalization of the TYDET program. The goal is to then identify the sources of the systematic errors that affect the TYDET such that they may be corrected to improve the overall forecast accuracy.

### 1. Overall Performance of TYDET for All Storms

The best-track data from all storms that came within 360 n mi of Kadena AB (Figure 9) were input to TYDET to identify the average speed error. These speed errors were plotted at each grid point in the TYDET program (Figure 11). Because of the very small number of TCs that passed close enough to Kadena AB, the inner grid was not analyzed. The overall pattern of speed error tends to be in four quadrants with positive errors in the west-northwest and southwest and negative errors in the east-northeast and south-southwest.

The pattern can likely be attributed to the typical TC track, which is from the south and passes to the west of Kadena AB. These tracks indicate that Kadena AB will be in the right-front quadrant of the TC when the storm is south or southwest of Kadena AB (Figure 12) and Kadena AB will be in the right-rear quadrant as the TC moves to the west, northwest, and the northeast of Kadena AB (Figure 13).

The TYDET forecasts were then analyzed based on which TC quadrant was affecting Kadena AB to examine how the storm approach direction contributes to the errors. Speed errors when Kadena AB is in the right-front quadrant of the TC (Figure 14) also have positive values to the west of Kadena AB and negative error values to the south. It is also useful to analyze the wind errors by u- and v-components to examine the separate contribution to runway cross-wind errors as a function of storm approach direction. The errors in the forecast u-component (Figure 15) and the v-component (Figure 16) at Kadena AB indicate that the total speed errors are primarily due to errors in the meridional wind. The errors in the u-component are opposite in sign to the speed and v-component errors such that negative errors are found when the storm is to the west of Kadena AB and positive values are found when the storm is to the south.

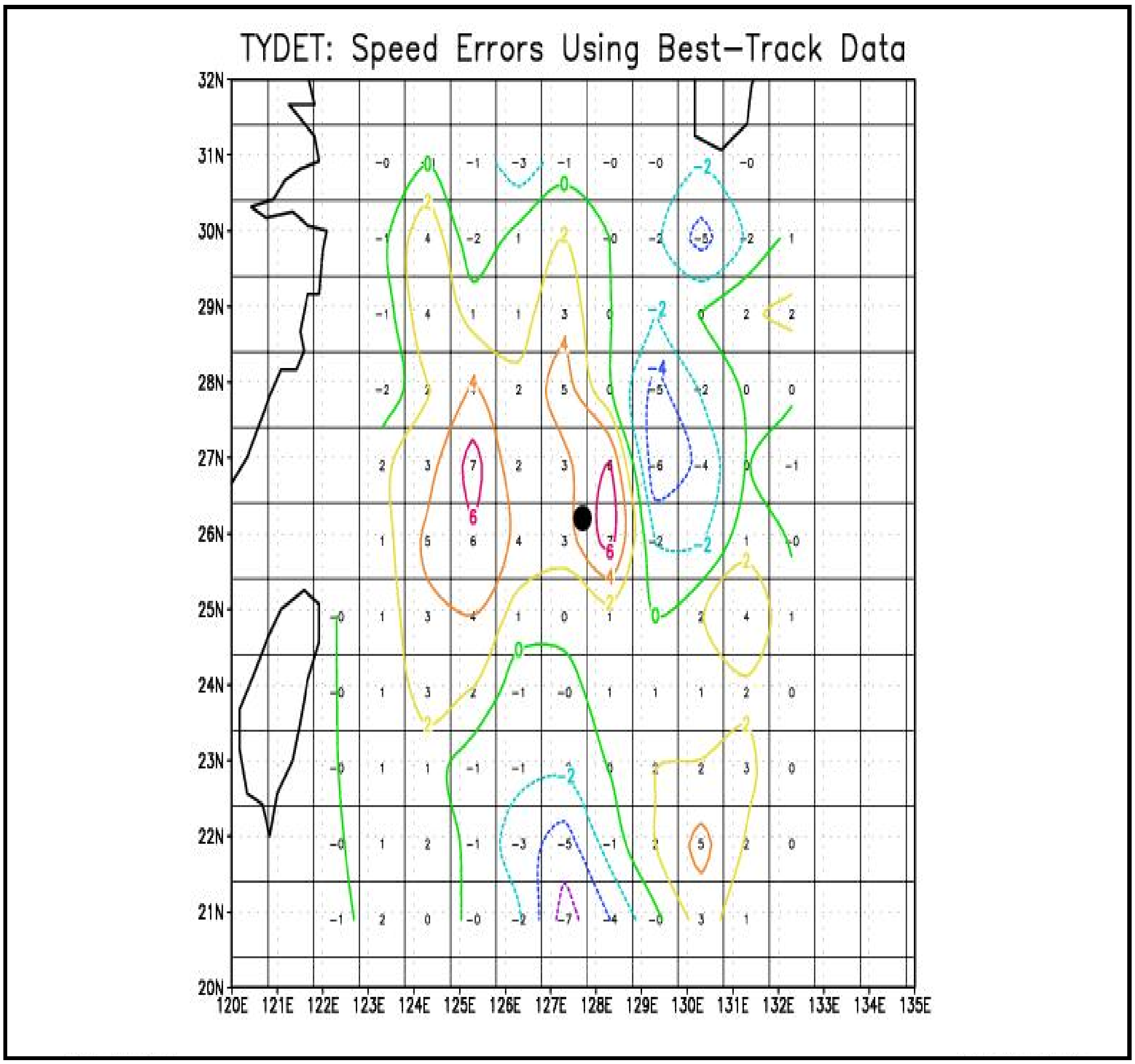


Figure 11. Overall speed errors (kt) for TYDET forecast from JTWC best-track data compared to observed wind speeds. For this and subsequent plots, contours are based on the application of a nine-point smoother to the TYDET grid.

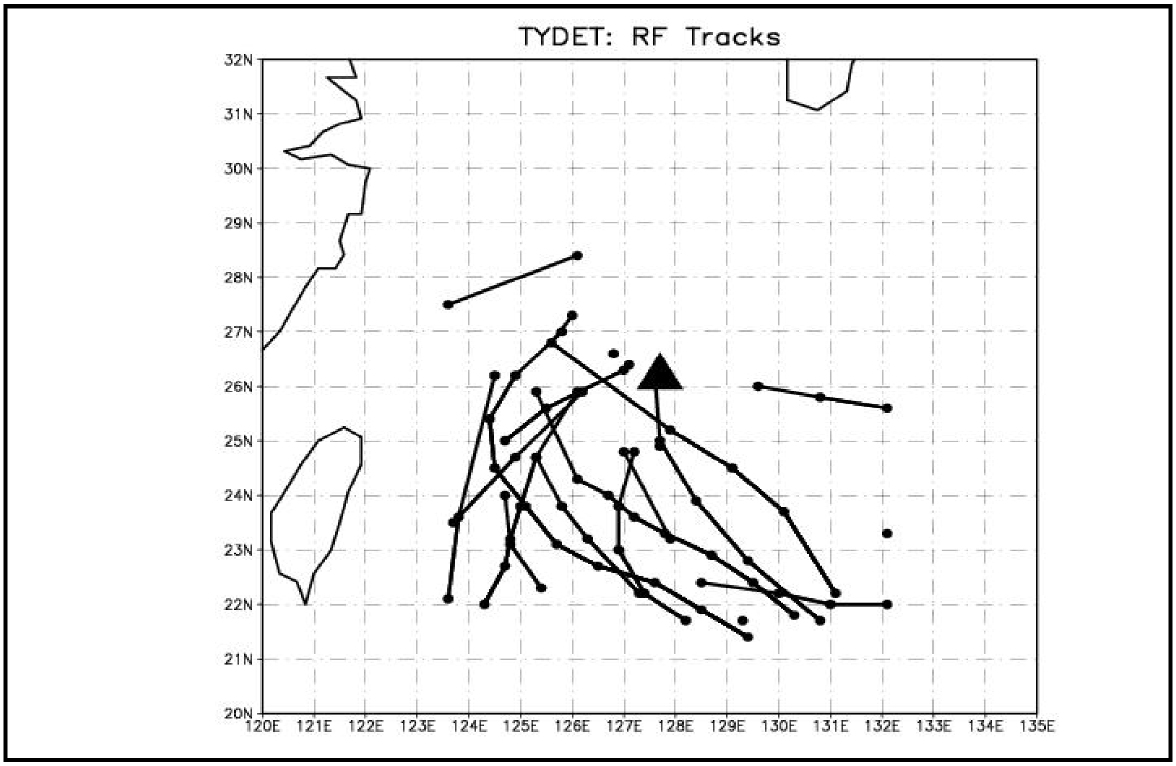


Figure 12. Best-track positions (6-h intervals) of right-front quadrant of storms within 360 n mi of Kadena AB between 2001 and 2005.

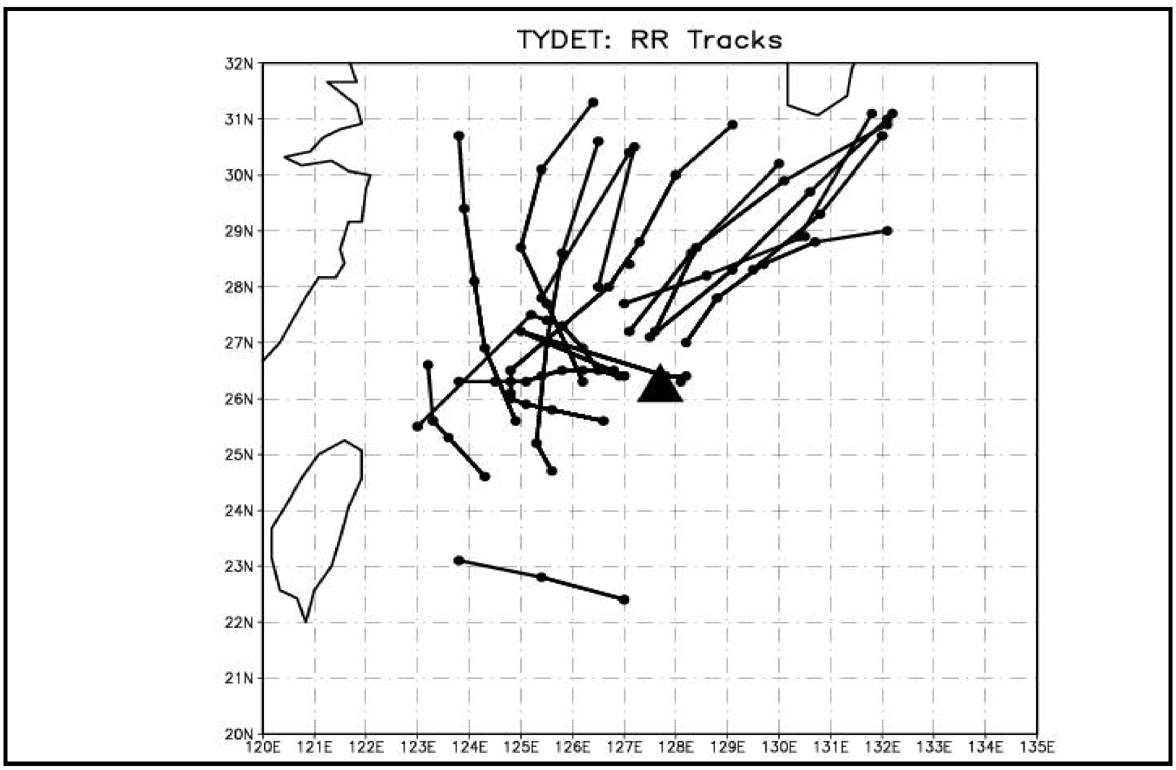


Figure 13. As in Figure 12, except for storms in which Kadena AB is in the right-rear quadrant.

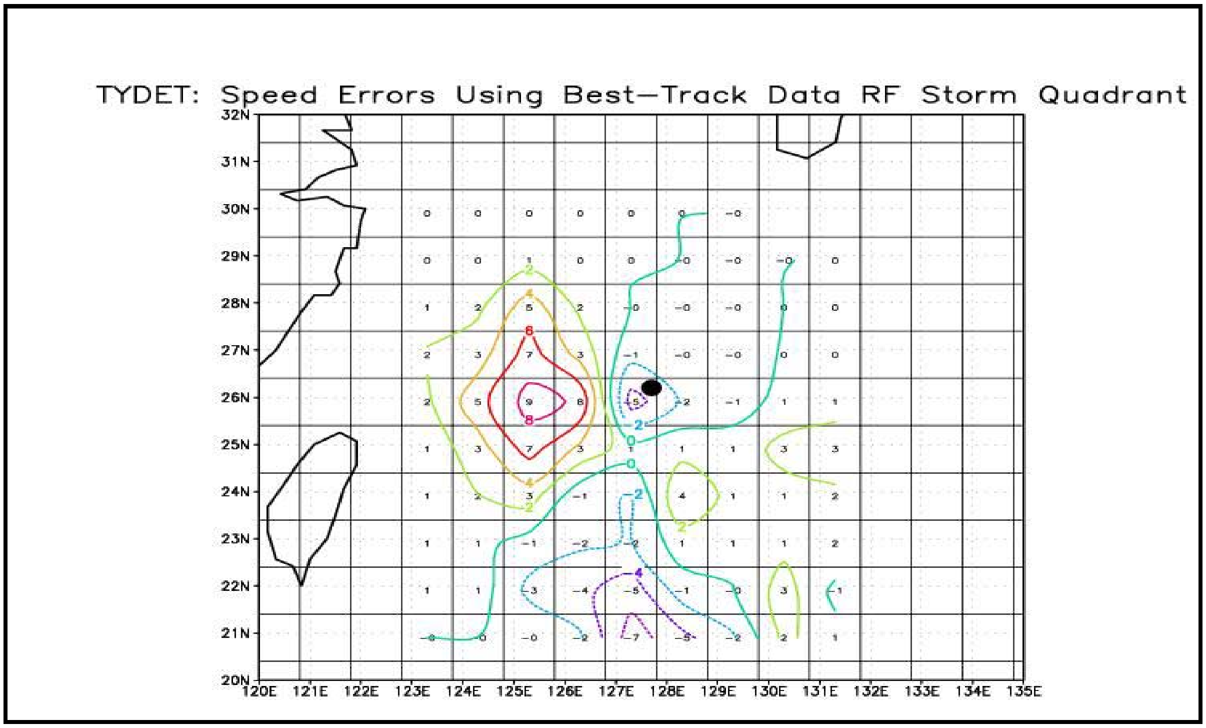


Figure 14. Overall speed errors (kt) for TYDET forecasts from JTWC best-track data when Kadena AB is in the right-front quadrant of the TC.

When a TC is southeast of Okinawa so that Okinawa is in the right-front quadrant of the storm, the forecast wind speeds are too strong (Figure 14). In this case, Okinawa would typically experience winds with an easterly zonal component and a northerly meridional component. The u-component error (Figure 15) indicates that the easterly component is too weak and the v-component error (Figure 16) indicates the northerly component is much too strong.

When a TC is directly south of Okinawa and at a large range, easterly winds would be expected at Kadena AB and the u-component error (Figure 15) indicates that the easterly component of the wind would be too weak. When the TC is at large distances south of the island, the meridional winds are too southerly (Figure 16). However, the meridional winds at smaller distances are too northerly.

As a TC proceeds west of Okinawa, the forecast speeds are too strong (Figure 14). In this case, Kadena AB would likely experience southerly winds. The u-component errors (Figure 15) indicate that these forecasts have an erroneous easterly component. Also, the southerlies are too strong (Figure 16).

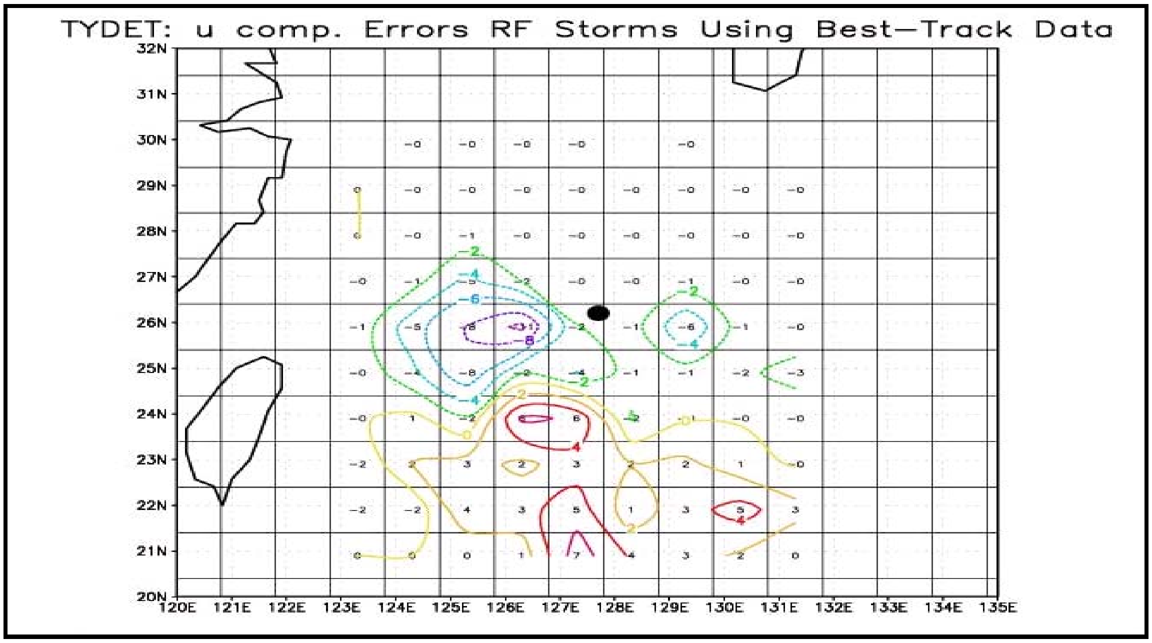


Figure 15. The u-component errors (kt) for TYDET forecast from JTWC best-track data when Kadena AB is in the right-front quadrant of the TC.

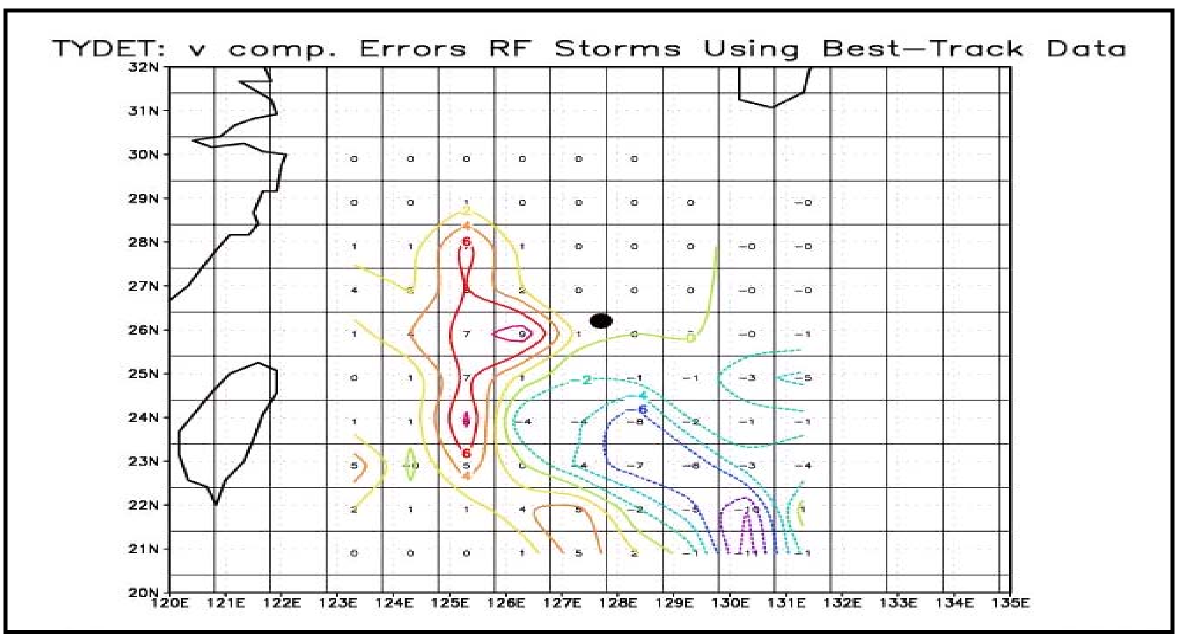


Figure 16. The v-component errors (kt) for TYDET forecast from JTWC best-track data when Kadena AB is in the right-front quadrant of the TC.

The errors were also defined for cases in which Kadena AB was in the right-rear quadrant (Figure 17). For a TC that is west of Okinawa such that Kadena AB is in the right-rear quadrant, the forecast wind speeds are too strong (Figure 17). When a TC is west of Okinawa so that Okinawa is in the right-rear quadrant, southerly or southeasterly winds would be likely at Kadena AB. The u-component errors (Figure 18) indicate that the forecasts have too large of a westerly component. The errors in the v-component (Figure 19) indicate that the meridional winds have a southerly component that is too small.

When a TC moves to the northwest of Okinawa, the wind speed forecasts are also too strong. For this storm position, Okinawa would expect a westerly wind with some southerly component. The errors in u (Figure 18) indicate that the forecast westerly winds are too weak and the errors in v (Figure 19) indicate that the forecast southerlies are also too weak.

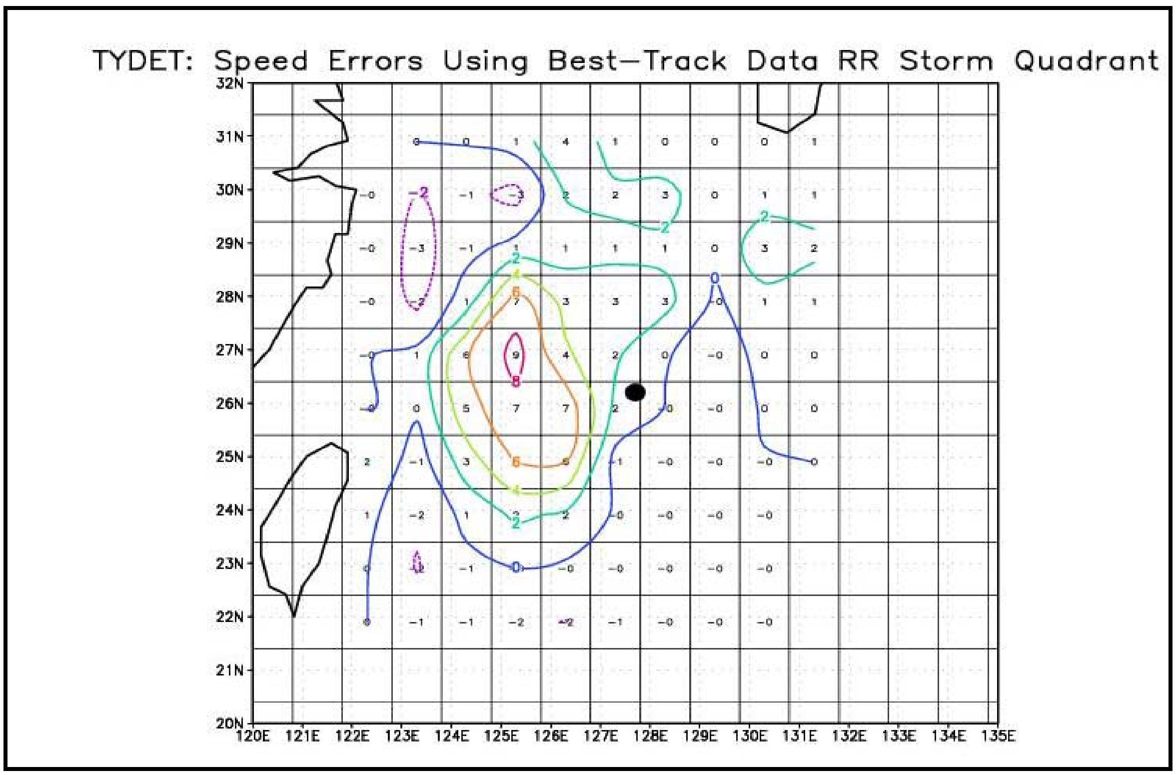


Figure 17. Overall speed errors (kt) for TYDET forecasts using JTWC best-track data when Kadena AB is in the right-rear quadrant of the TC.

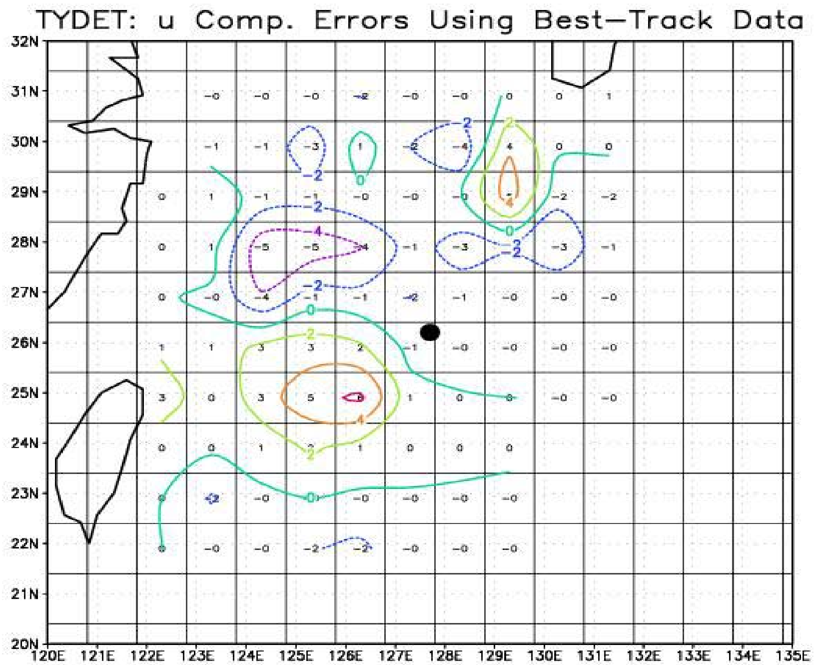


Figure 18. The u-component errors (kt) for TYDET forecasts using JTWC best-track data when Kadena AB is in the right-rear quadrant of the TC.

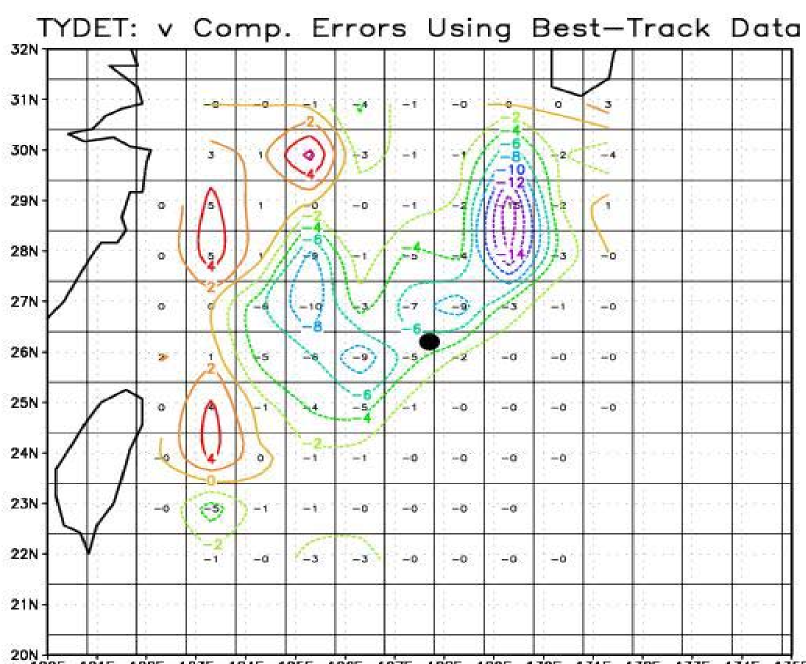


Figure 19. The v-component errors (kt) for TYDET forecasts using JTWC best-track data when Kadena AB is in the right-rear quadrant of the TC.

The storm approach direction has an effect on the extent of the speed, u-component, and v-component errors within TYDET-based forecasts. By examining the storm approach direction and the storm relative quadrant that affects Kadena AB using best-track data, some of the systematic TYDET errors become apparent. These systematic errors must also be examined to determine if other parameters may be involved in creating the TYDET forecast errors.

### 2. Overall Performance of TYDET With Respect to Size

In Section II.C.1., a systematic error in wind speed forecasts for TYDET was identified such that speeds are over-forecast when a TC passes west of Kadena AB and under-forecast when a TC passes south of Kadena AB. Although storm track and direction of approach to Kadena AB thus contribute to errors in TYDET forecasts, other sources may contribute to TYDET errors. One of these sources is storm size, which can fluctuate greatly from the time of genesis to the time of dissipation. Storm size is defined here as the sum of the four quadrant radii of the 34-knot winds. It is apparent that a larger storm will impact Kadena AB from a farther distance than a small storm. Because the TYDET program was derived from a sample of many storm sizes, it will forecast winds at Kadena AB that are representative of an average size storm. Thus, a small storm would tend to have TYDET forecast winds that are overestimated, especially when the storm is far from Kadena AB.

Recall that the majority of TCs affecting Kadena AB follow a track that passes south and then west of Okinawa. For small storms that are far south of Okinawa, the speed errors (Figure 20) are negative, as expected from the discussion above. For small storms that pass to the west (east) of Okinawa, the overall wind speeds are too strong (weak). Similarly, for large storms that are west and northwest of Kadena AB, the wind speed forecasts (Figure 21) are too strong. Based on these wind speed error patterns for small and large storms, it is concluded that size is a contributing factor to the TYDET wind speed error as the TC passes south of Okinawa and when the TC passes to the west of the island. A positive overall wind speed error exists for all storms (Figure 11), small storms (Figure 20), and large storms (Figure 21).

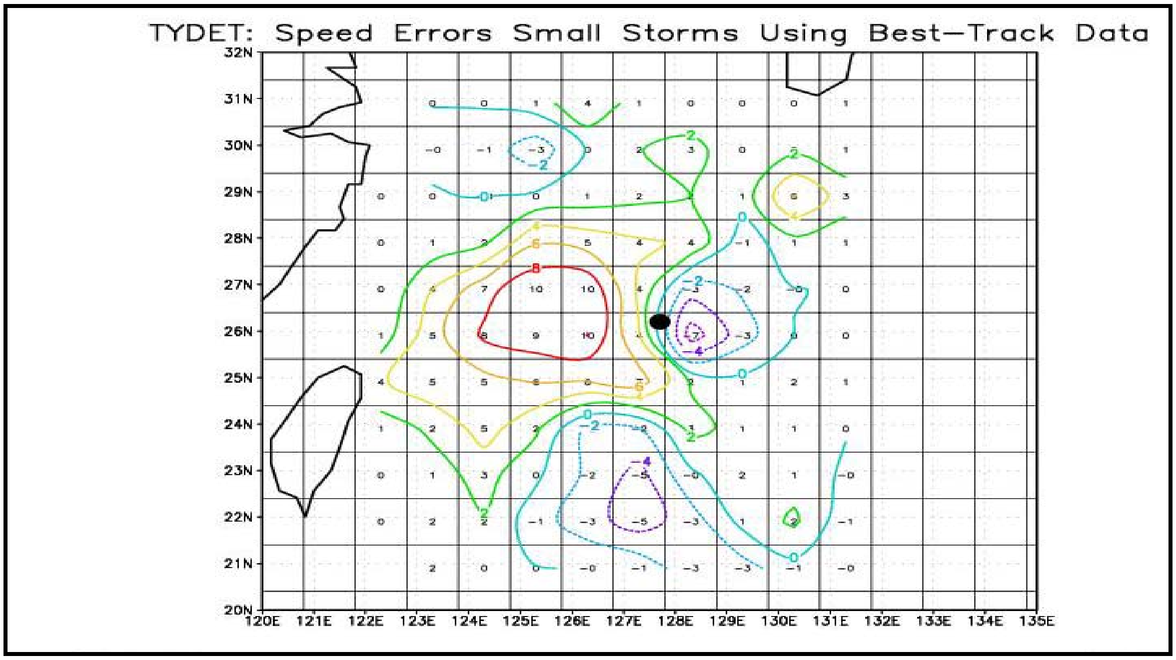


Figure 20. Overall speed errors (kt) for small storms for TYDET forecasts using best-track data.

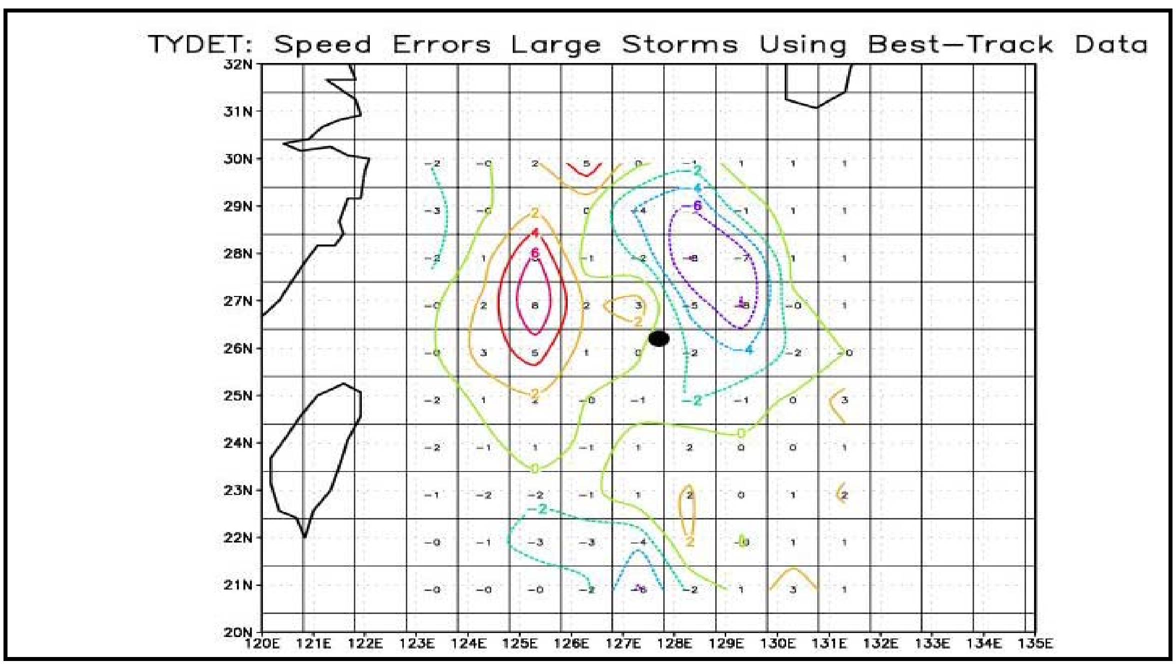


Figure 21. Overall speed errors (kt) for large storms for TYDET forecasts using best-track data.

As in Chapter II.C.1., the TYDET errors will again be examined in the storm-relative quadrants to determine the effect of storm approach direction. Enough cases exist along the primary storm track as the TCs pass west and north of Okinawa. When Kadena AB is in the right-front quadrant of a small storm (Figure 22), there are positive errors if the storm is to the southwest of Kadena AB, but negative errors if the storm is well to the south. Since the error to the south in Figure 22 is very similar to that in Figure 20, the storm size is a larger contribution to the TYDET error than is due to the storm approach direction. When Kadena AB is in the right-rear quadrant of a small storm (Figure 23), maximum wind speed errors occur when the storm is just west or to the north.

For large storms, 34-knot winds will extend out farther from the center and affect the island from farther away. Given the same storm location and the same overall intensity, the larger storm will produce stronger winds at Kadena AB than the small storm. When Kadena AB is in the right-front quadrant of large storms (Figure 24), an approach from the south will lead to negative (too small) TYDET winds, especially when the large storm is just to the southwest of Okinawa. However, positive errors are found if the storm is approaching more from the western area such that Okinawa is still in the right-front quadrant. Larger positive errors are found if the large storm is to the northwest of Okinawa so that it is in the right-rear quadrant (Figure 25). Since these positive errors are contrary to the expectation for large storm, this error must be attributed to the storm track direction (see positive values in Figure 17). That is, when the large storm is to the west a less positive speed error will occur than would have occurred for an average size storm. This would explain why the positive errors to the west decrease and the negative values to the extreme south become more negative.

As in Chapter II.C.1., examining the TYDET wind errors in u- and v-components will assist in understanding runway cross-wind errors. When Kadena AB is in the right-front quadrant of a small storm, the u-component errors (Figure 26) are negative when the approaching storm is to the west and small positive when the approaching storm is to the south. When an approaching storm is just to the west-southwest of Kadena AB, an easterly u-component would be expected at Kadena AB. If the TC is small, the negative u-component error in Figure 26 indicates that the winds at Kadena have too small of an easterly component.

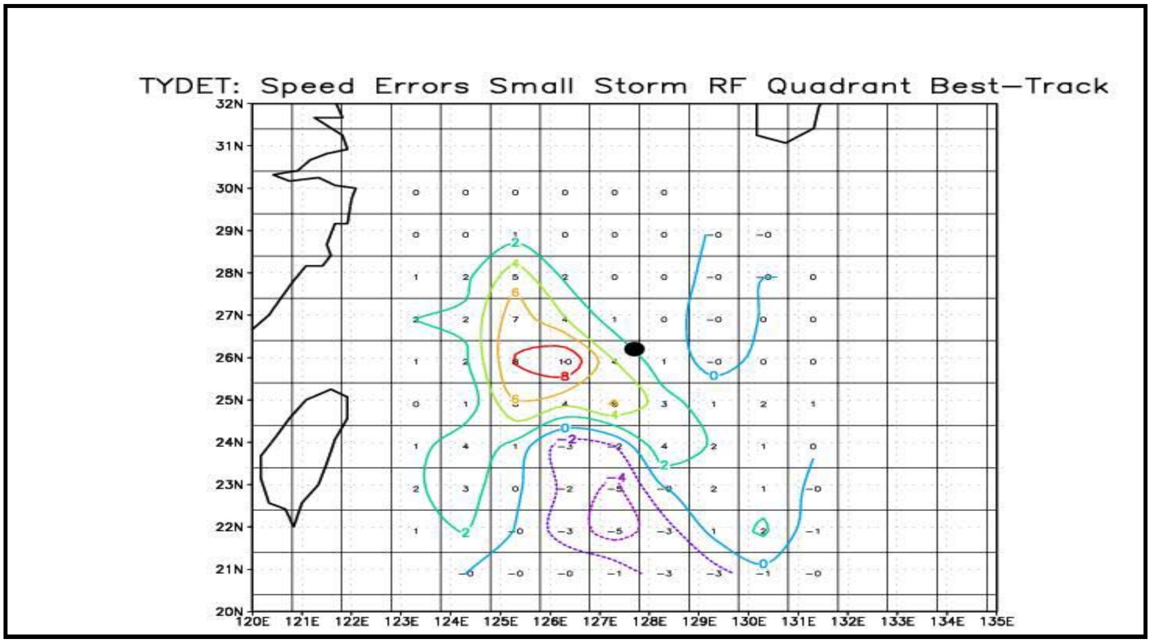


Figure 22. The wind speed errors (kt) in TYDET based on JTWC best-track data for all small storms with the right-front quadrant affecting Kadena AB.

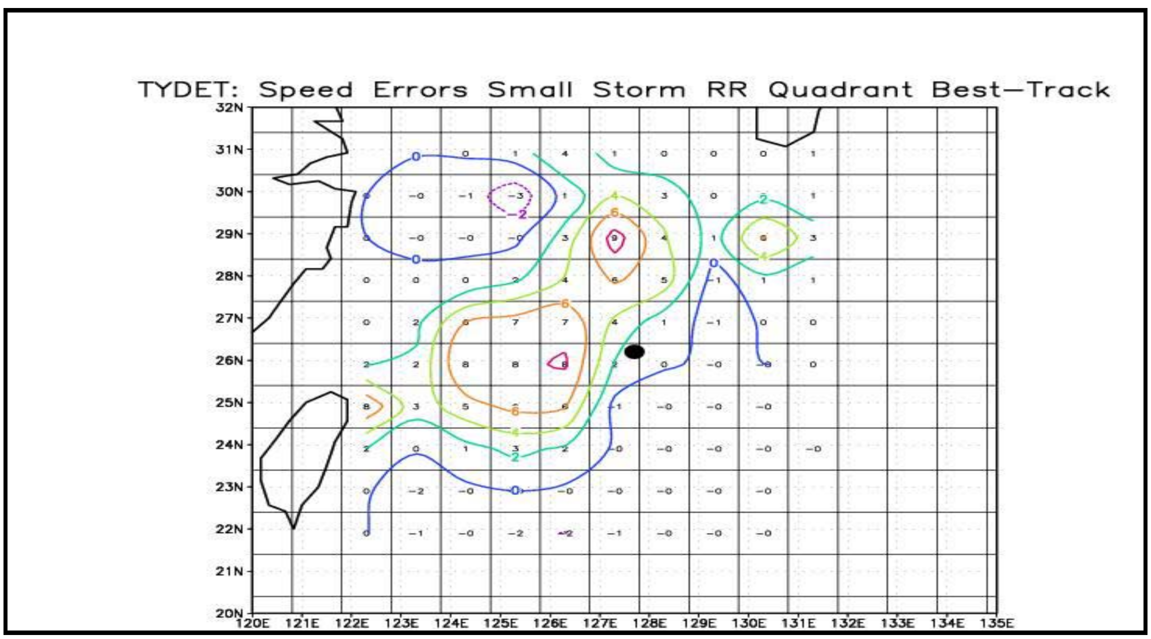


Figure 23. The wind speed errors (kt) in TYDET based on JTWC best-track data for all small storms with the right-rear quadrant affecting Kadena AB.

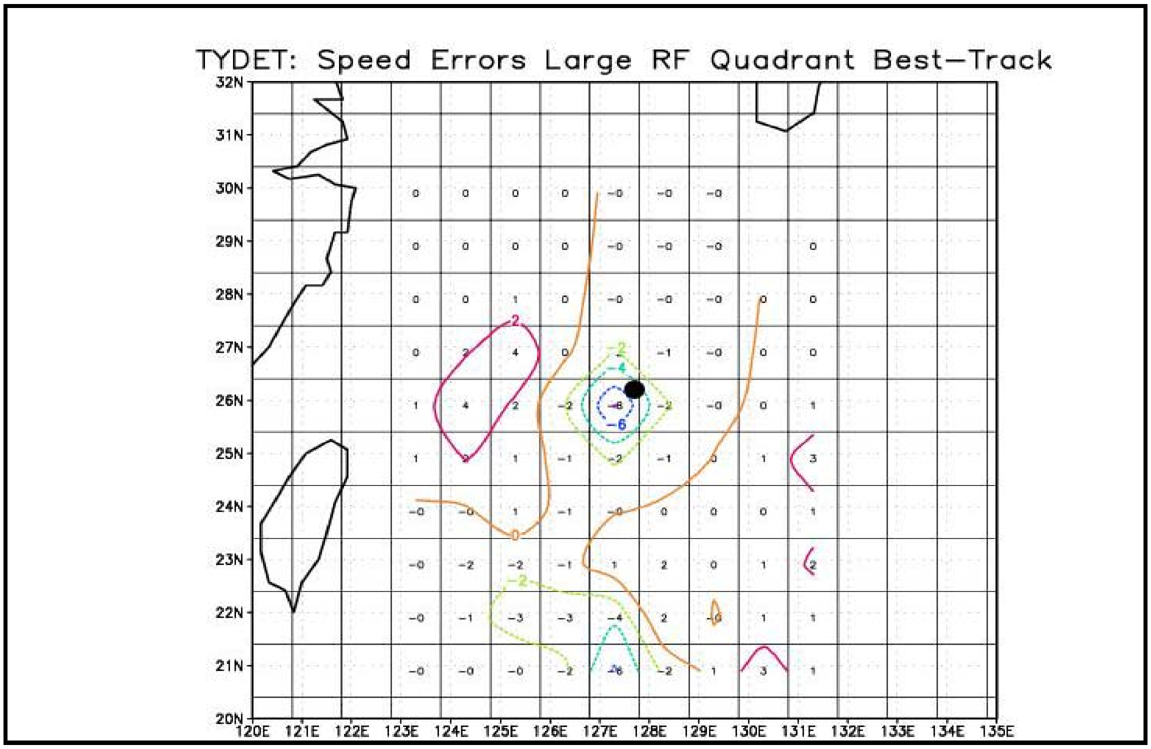


Figure 24. The wind speed errors (kt) in TYDET based on JTWC best-track data for all large storms with the right-front quadrant affecting Kadena AB.

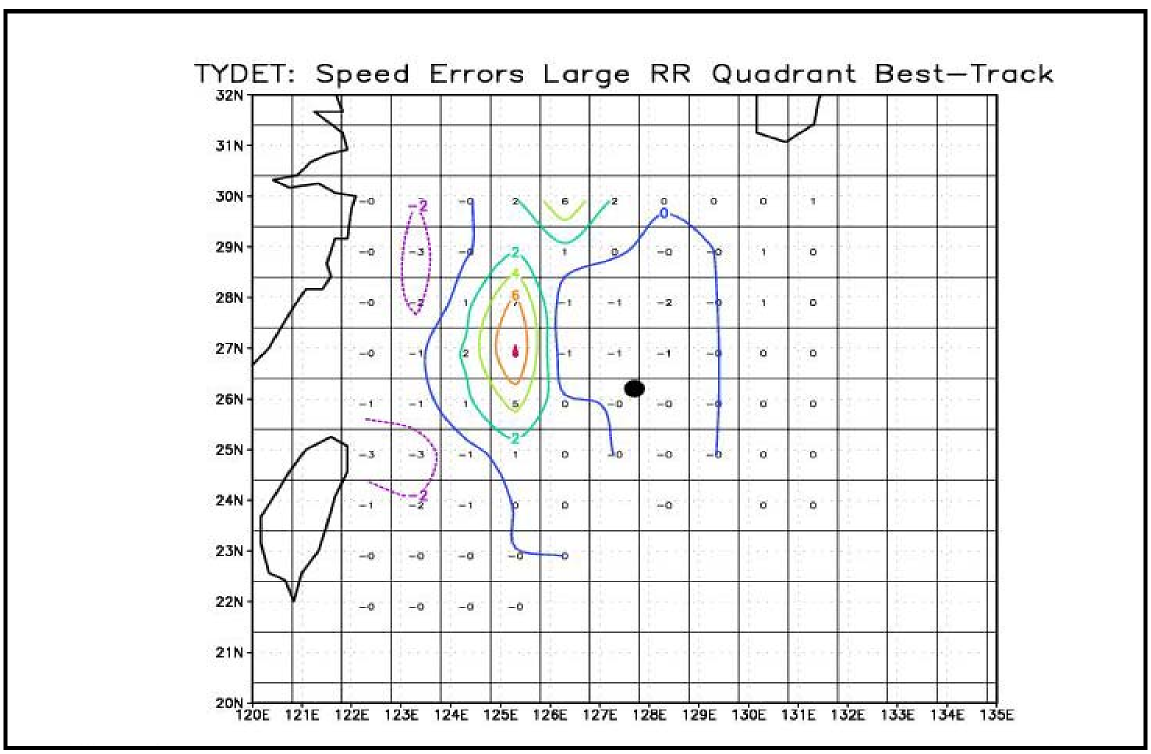


Figure 25. The wind speed errors (kt) in TYDET based on JTWC best-track data for all large storms with the right-rear quadrant affecting Kadena AB.

The v-component error pattern (Figure 27) for a small storm just to the south-southwest of Kadena AB is the opposite of that in the u-component indicating that the southerly component of the winds at Kadena AB is forecast to be too strong. This is due to the small storm having less radial extent and therefore impacting Kadena AB less than the TYDET program calculates. The large negative maxima to the southeast (Figure 27) of Okinawa cannot be explained through size effects alone. It is expected that the southerly component would be forecast to be to strong, but the opposite is true.

The patterns in u and v-component errors (Figures 28 and 29) for large storms for the right-front quadrant cases differ from the small cases, especially in that the magnitude of the errors is smaller for large storms. When the storm is to the west of Okinawa, the larger outward extent of the storm causes the underestimated (negative values) easterly component to be reduced (Figure 28). When the storm is to the west of Okinawa, the southerly component (Figure 29) error is also reduced. In this case, the southerlies increase and the TYDET forecast is no longer too strong due to the increased storm size. When the storm is to the south of Okinawa the forecast easterly component (Figure 28) goes from being too large (small storm) to too small. This indicates that the storms winds are influencing Okinawa to a greater extent than is the small storm case. The TYDET forecast still represents the southerly component of the winds to be too weak and it appears that the large negative maxima has shifted farther south when compared with Figure 27. This could be due to storm track and less due to size.

The hypothesis that TYDET would overestimate wind speeds for small storms is correct for storms to the west, but not for storms to the south where the winds are underestimated. Also, the patterns for the u- and v-component errors cannot entirely be attributed to storm size differences. Therefore, it can be concluded that storm size is not the only parameter that must be considered when examining TYDET forecast errors.

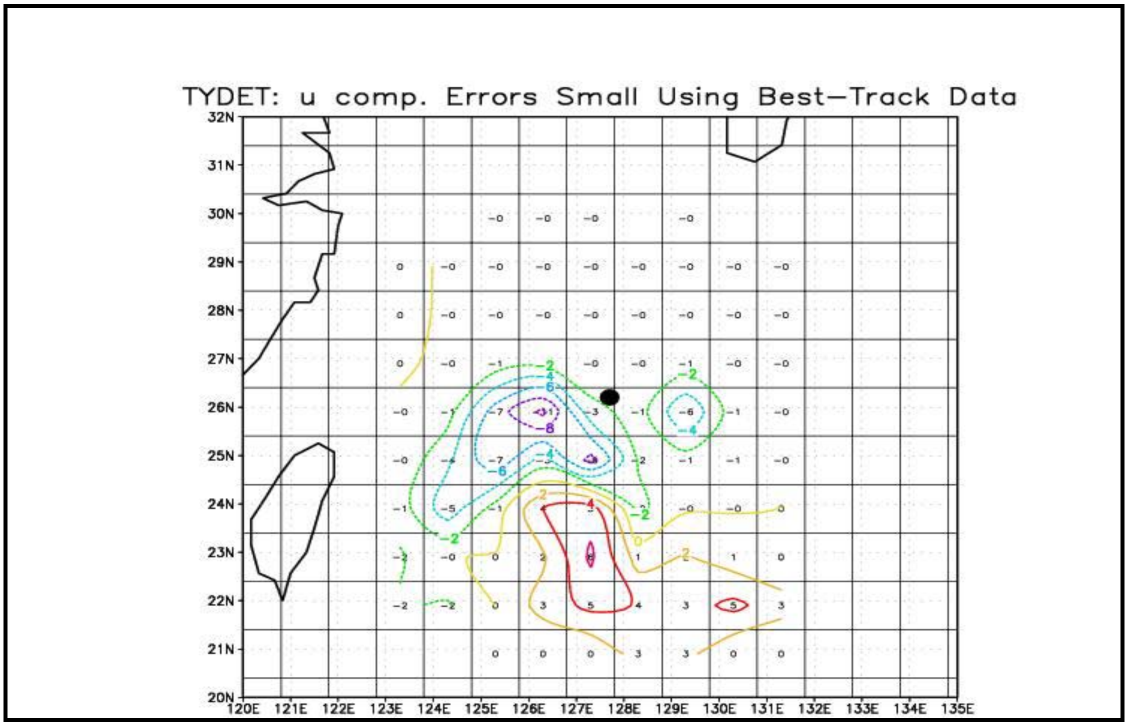


Figure 26. The u-component errors (kt) in TYDET based on JTWC best-track data for the small storms with the right-front quadrant affecting Kadena AB.

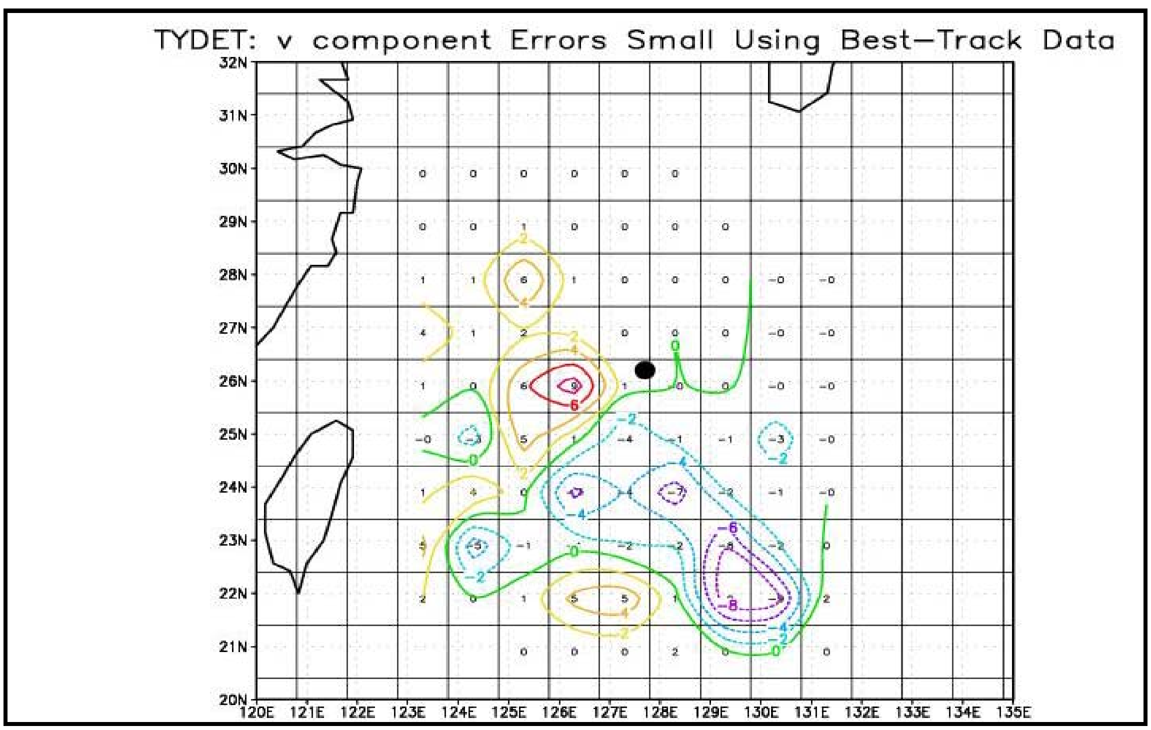


Figure 27. The v-component errors (kt) in TYDET based on JTWC best-track data for the small storms with the right-front quadrant affecting Kadena AB.

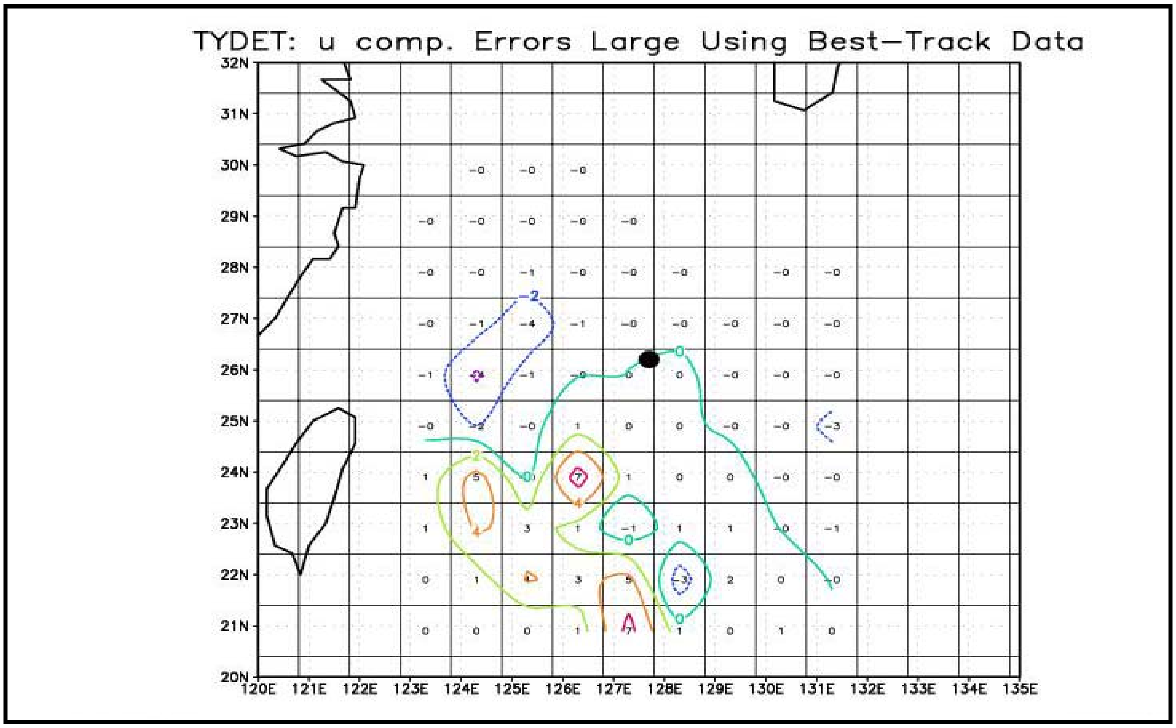


Figure 28. The u-component errors (kt) in TYDET based on JTWC best-track data for the large storms with the right-front quadrant affecting Kadena AB.

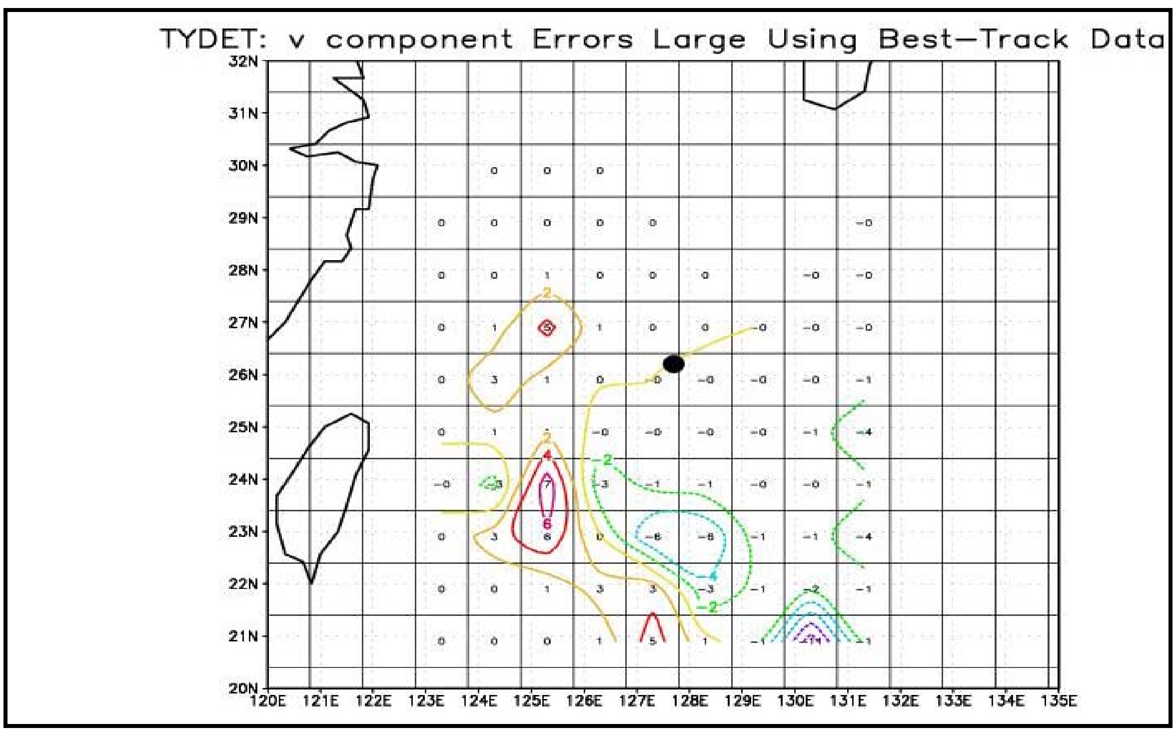


Figure 29. The v-component errors (kt) in TYDET based on JTWC best-track data for the large storms with the right-front quadrant affecting Kadena AB.

### 3. Overall Performance of TYDET With Respect to Size and Symmetry

Wind speed errors were examined for small-symmetric, small-asymmetric, large-symmetric and large-asymmetric storms. Patterns of the wind speed errors for small-symmetric storms (Figure 30) are similar to those of all storms (Figure 11) in that the wind speeds are over-forecast when the storm was to the west of Okinawa and under-forecast when the storm was to the south of Okinawa. The small-asymmetric TC may have one quadrant that reaches the criterion for being a large storm, but the sum of the quadrants still puts the storm in the small category. Kadena AB tended to be in the right-front storm quadrant when a TC was passing south of Okinawa. Wind speed errors associated with these cases are all negative (Figure 31), as the asymmetric extension of the winds in the right-front quadrant is underestimated. The right-front quadrant tended to be largest quadrant of a small-asymmetric TC when it was moving northward. When a small-asymmetric TC passes west of Kadena AB, the wind speed errors are over-forecast, which is an overwhelming systematic bias in TYDET.

For a large-symmetric TC (Figure 32), the wind speed forecast errors are less positive when the storm is to the west of Kadena AB than for the small-symmetric storms, which indicates that the greater extent of winds in large TCs has offset the systematic error (over-forecast winds to the west of Okinawa) within the TYDET wind forecast. The wind speed errors for large-asymmetric cases (Figure 34) exhibit the same patterns as the small-asymmetric case in that the storms to the south (where the right-front quadrant of the storm influences Kadena AB) result in wind speed forecasts that are too low. Again this is due to the larger winds being in the quadrant to the northeast of the storm and thus the storm influences Kadena AB more than the original TYDET forecast would indicate. As the storm moves to the west of Kadena AB, the right-rear storm quadrant, which tends to have the smaller winds than the other quadrants, begins to dominate and the TYDET wind speeds are then an over-forecast.

When the right-front quadrant of a small-symmetric storm (Figure 34) influences Kadena AB, the wind speeds are underestimated when the storm is to the south and overestimated when the storm is to the west. As the TC passes to the northwest and north, the right-rear quadrant (Figure 35) impacts Kadena AB and the TYDET wind speeds are overestimated. When the right-front quadrant of a small-asymmetric (Figure 36) TC affects Kadena AB, the wind speeds when the storm is to the south are still underestimated and the winds when the storm is in close proximity to Kadena AB are overestimated. This is because the small-asymmetric TC has a smaller radial extent than the TYDET sample average. When the right-rear quadrant of a small-asymmetric (Figure 37) TC affects Kadena AB the wind speeds are overestimated when the storm is to the west and north. This is because the smaller right-rear quadrant is not affecting Kadena AB as much as forecast.

Overall wind speeds at Kadena AB that are estimated by TYDET have exhibited large systematic errors that depend on the relative location of the TC, the heading of the TC, the radial distance of the TC from Kadena AB, the size of the TC, and the symmetry of the TC. Because these errors were identified by using the best-track TC location and maximum wind speed as input to TYDET, these errors are attributed to the internal formulization of the TYDET tables. In the following section, TYDET is evaluated when JTWC forecast TC location and intensity are used as input as would be done in an operational environment.

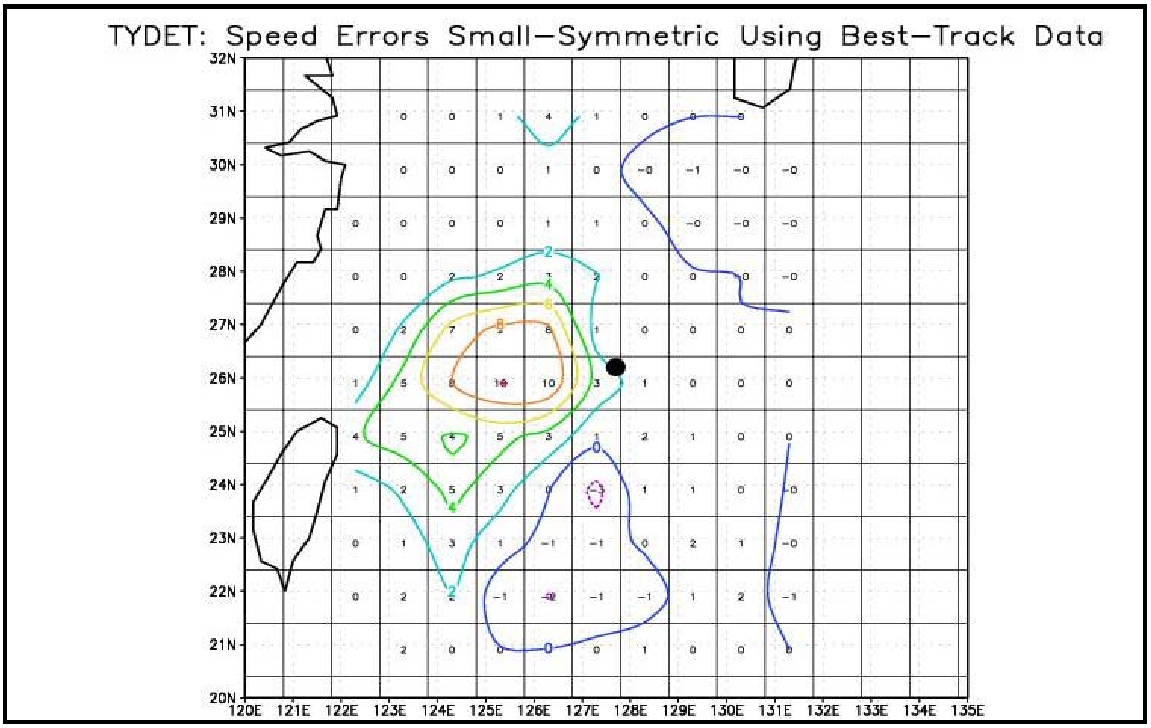


Figure 30. The wind speed errors (kt) in TYDET based on JTWC best-track data for small-symmetric storms.

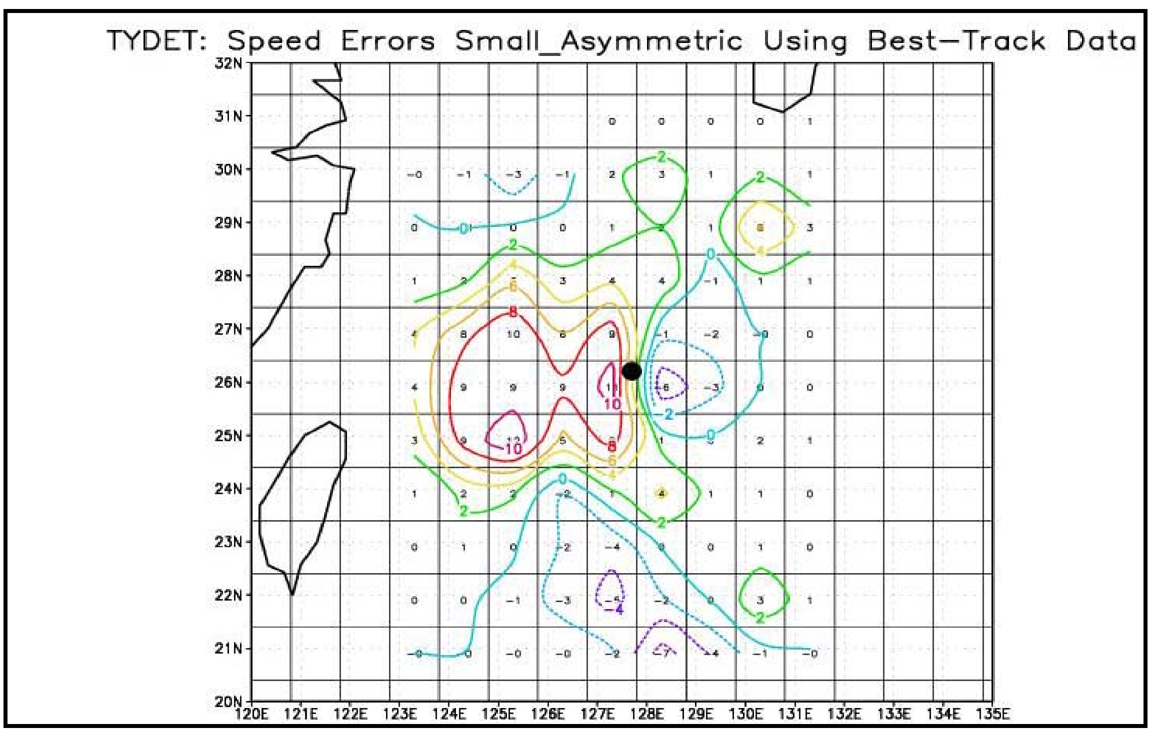


Figure 31. The wind speed errors (kt) in TYDET based on JTWC best-track data for small-asymmetric storms.

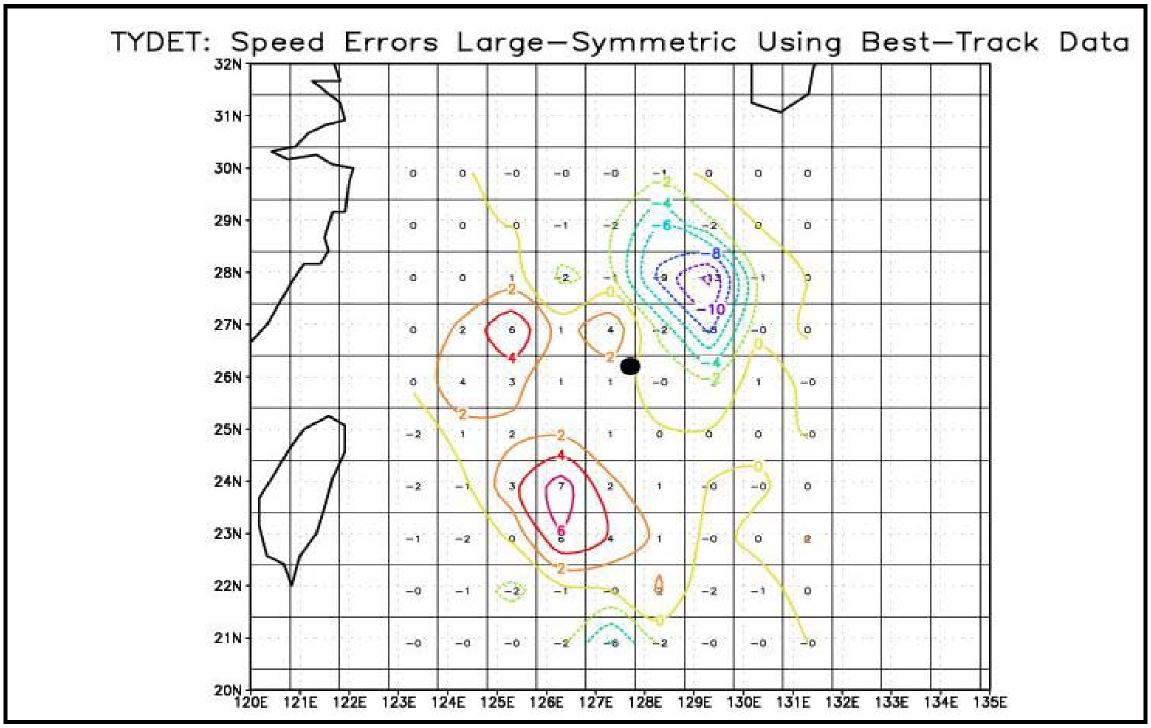


Figure 32. The wind speed errors (kt) in TYDET based on JTWC best-track data for large-symmetric storms.

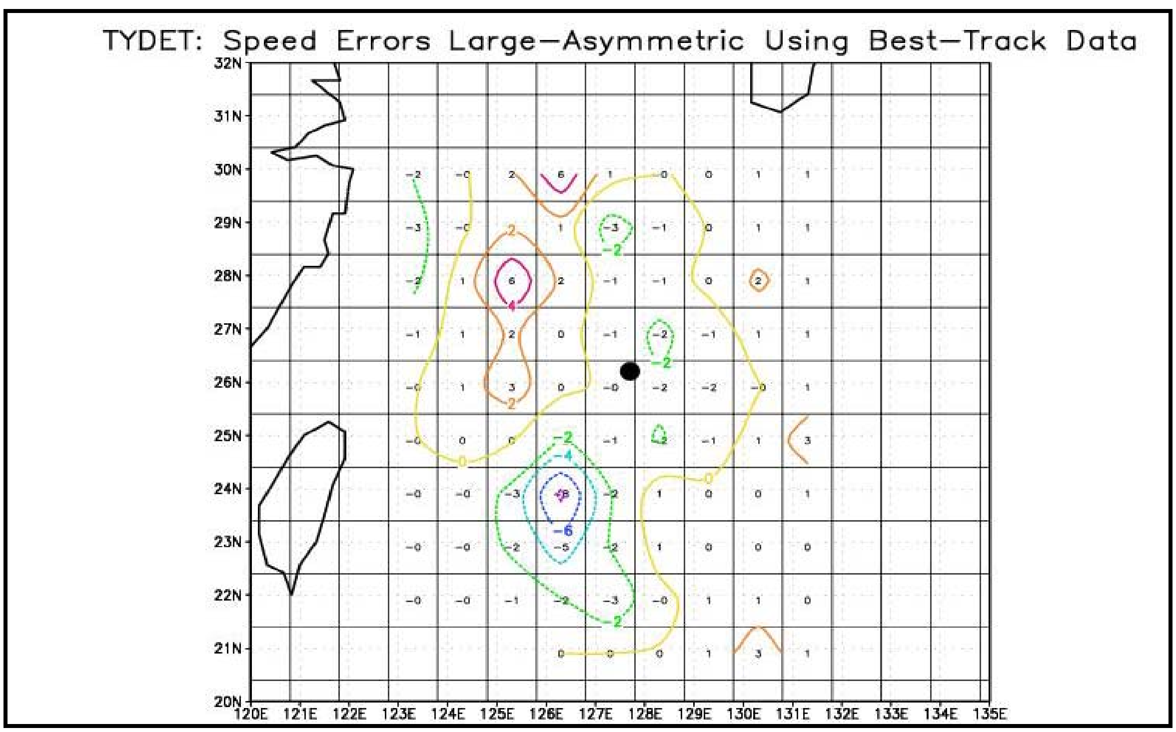


Figure 33. The wind speed errors (kt) in TYDET based on JTWC best-track data for large-asymmetric storms.

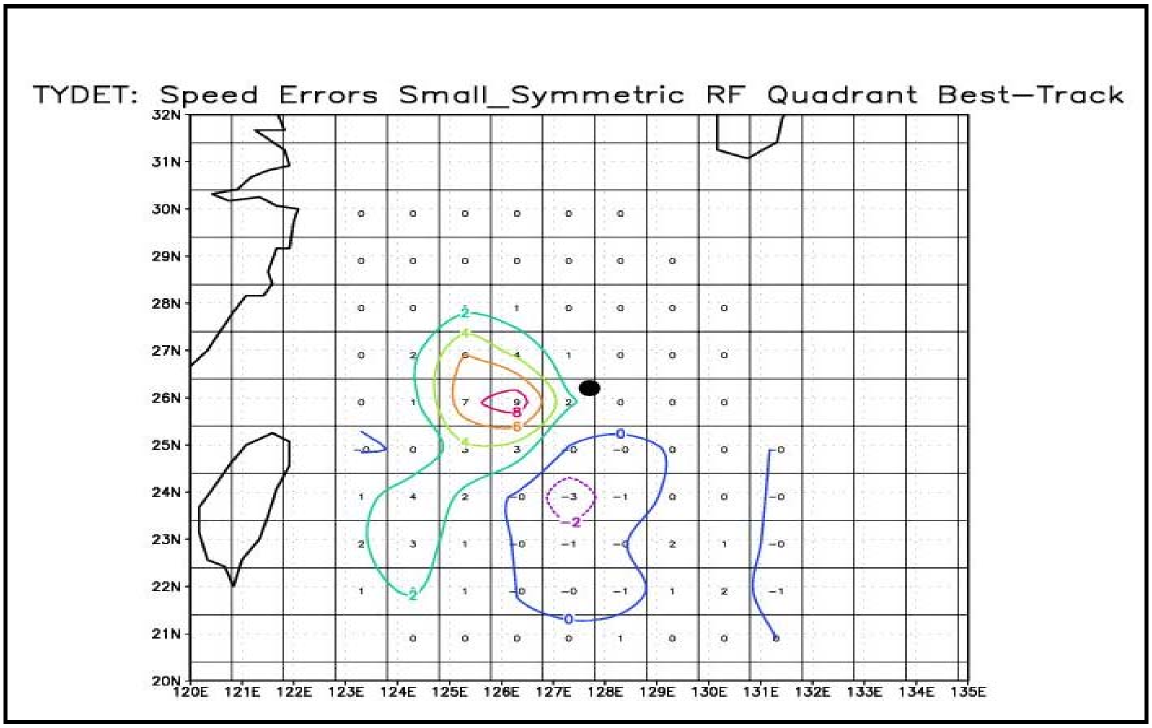


Figure 34. The wind speed errors (kt) in TYDET based on JTWC best-track data for small-symmetric storms with the right-front quadrant affecting Kadena AB.

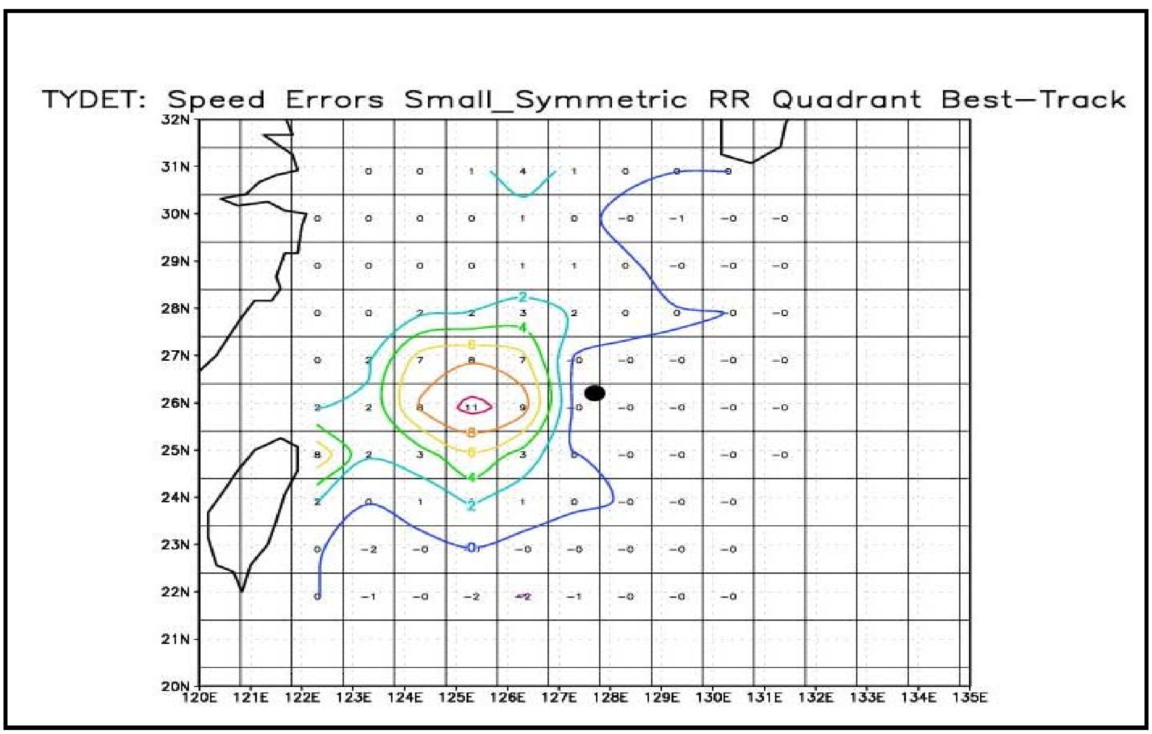


Figure 35. The wind speed errors (kt) in TYDET based on JTWC best-track data for small-symmetric storms with the right-rear quadrant affecting Kadena AB.

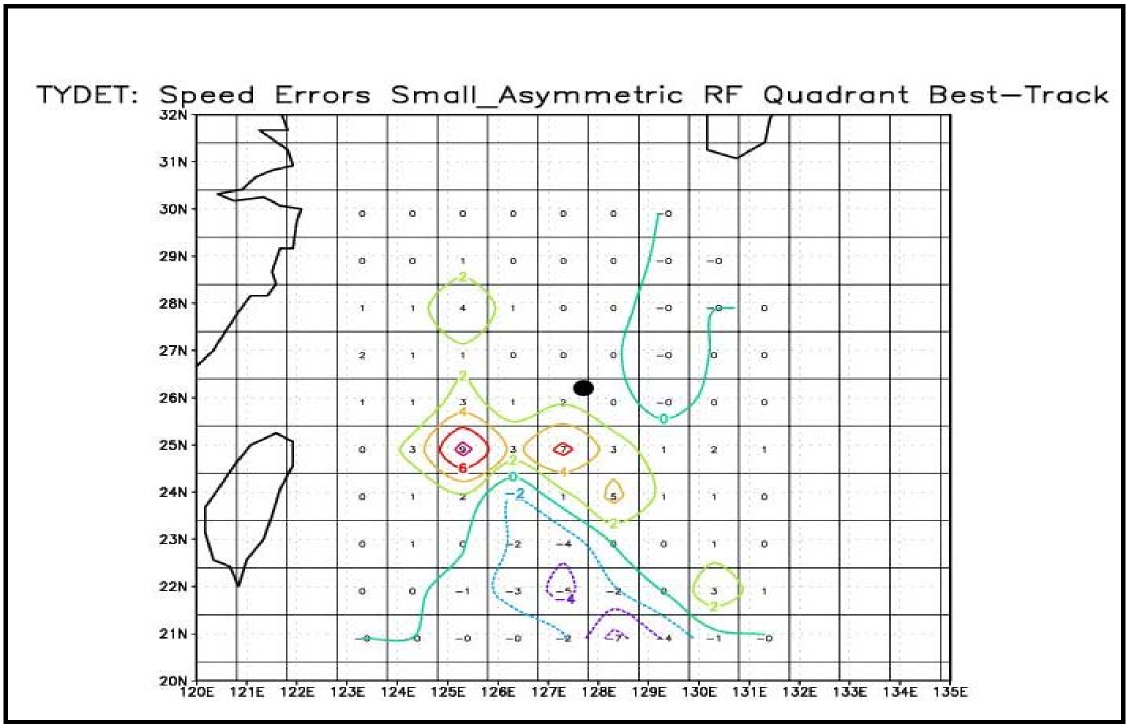


Figure 36. The wind speed errors (kt) in TYDET based on JTWC best-track data for small-asymmetric storms with the right-front quadrant affecting Kadena AB.

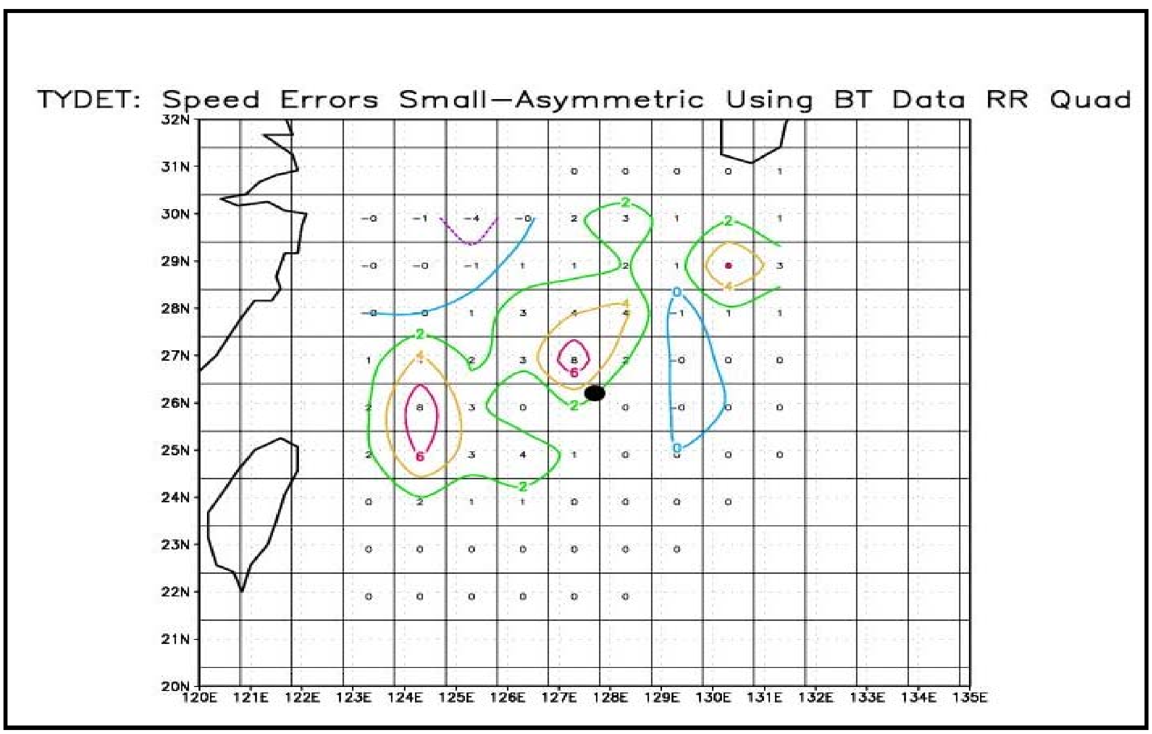


Figure 37. The wind speed errors (kt) in TYDET based on JTWC best-track data for small-asymmetric storms with the right-rear quadrant affecting Kadena AB.

## B. EVALUATING TYDET USING THE OFFICIAL JTWC FORECASTS

The best-track data were used to find the systematic errors within the TYDET program by using a "perfect" forecast. This portion of the study focused on using the same forecast information that is input to the TYDET program. This use of forecast inputs may have two effects. The first effect is that it may improve the TYDET forecast if the errors or biases in the JTWC forecast help to offset the errors inherent in the TYDET program. The other effect is that it may compound the error and produce even greater errors. The same methods were used to evaluate the TYDET forecast based on the JTWC forecast as were used to evaluate the TYDET forecast when best-track data were used. The examination of overall forecast accuracy with respect to the forecasts of location, wind speed, size, and symmetry included the 0-, 12-, 24-, 36-, 48- and 72-hour forecasts.

### 1. Errors in Location and Wind Speed

Additional sources of error in the TYDET program exist when the JTWC forecast is used to run the TYDET program. One source is the position error in the forecast, and thus an error in distance from Kadena AB, which determines which quadrant of the storm will be affecting the base, and which grid cell in TYDET the storm will occupy. As was demonstrated from the errors derived from best-track data, TYDET performance is sensitive to all of these parameters. Large TYDET forecast errors may be caused by the increase in forecast track errors that increase with forecast interval (Figure 38). An accurate track forecast is necessary for correctly predicting the range of the storm from Kadena AB. Large forecast track errors may result in a placement of the TC in a different quadrant relative to Kadena AB than observed. Although the quadrant is correctly forecast for the majority of cases (Figures 39 and 40), in many cases the quadrant is incorrect. Track forecast errors resulting in the storm being in the wrong quadrant also imply that the heading error or storm motion error may be large. These factors have already been identified as sources of possible large errors in TYDET.

The forecast accuracy associated with size and asymmetry are now examined with respect to their impact on TYDET. Because the speed errors were the most quantifiable and exhibited the largest errors, the impact on wind speed forecasts is also examined. Since the TYDET error patterns with the JTWC forecast were consistent throughout, the overall average speed error due to the JTWC forecast can be calculated and added to that arising from the best-track errors. Initially, the differences between the TYDET wind speed computed using the JTWC forecast and the TYDET wind speed computed using best-track data were examined for cases in which Okinawa was in the right-front and/or the right-rear quadrants (Figure 41) The differences increase as the forecast interval increases. The wind speed tends to be over-forecast for all 12-hour forecasts, but under-forecast at later forecast intervals, except for the right-front quadrant cases for which the wind speed is over-forecast until 36 hours. Therefore, the use the of the JTWC forecast TC position and wind speed as input to TYDET rather than the best-track (truth) data will result in an underestimate of the wind speed at Kadena AB.

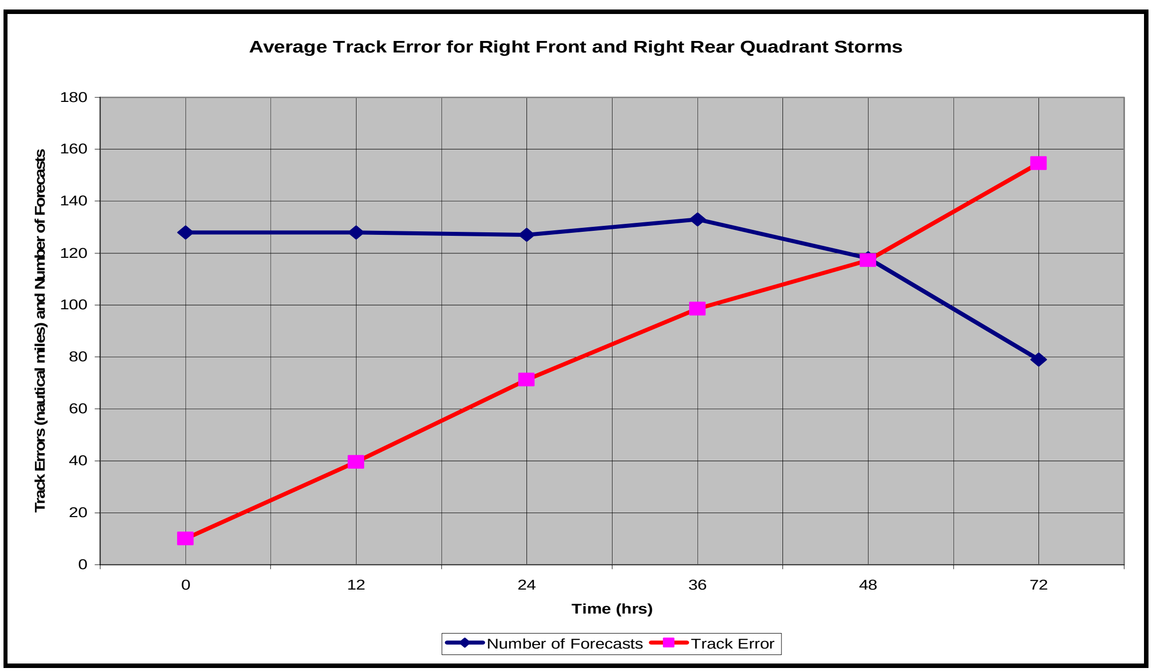


Figure 38. Average JTWC forecast track error (n mi; line with squares) when Kadena AB is in either the right-front or right-rear quadrant of the TC. The number of cases in the sample are indicated by the line with diamonds.

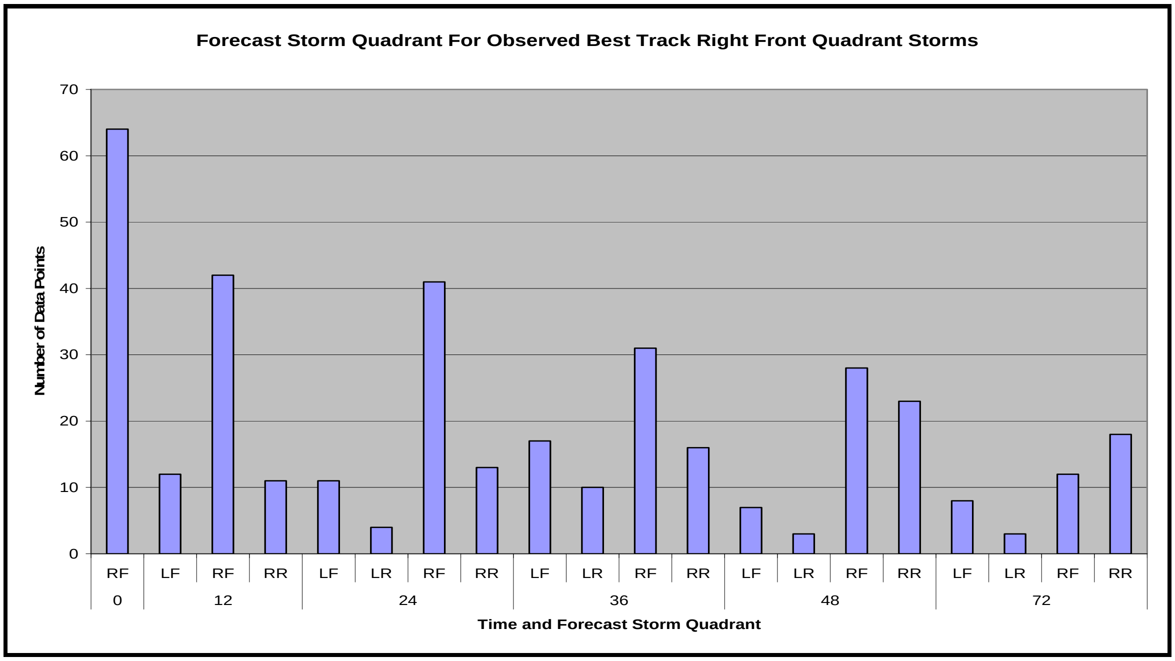


Figure 39. Frequency of correct and erroneous quadrants arising from JTWC track forecast for cases when Kadena AB was actually in the right-front quadrant of a TC. The bars along the abscissa indicate the forecast time the quadrants that were forecast for each forecast interval.

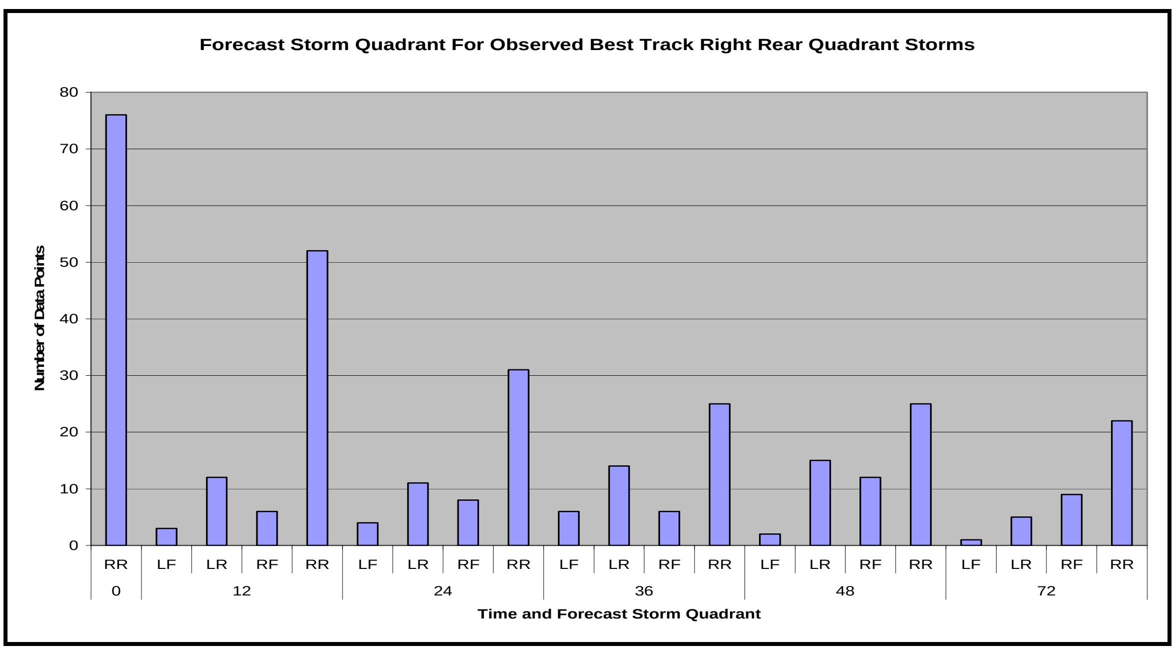


Figure 40. Frequency of correct and erroneous quadrants arising from JTWC track forecast for cases when Kadena AB was actually in the right-rear quadrant of a TC. The bars along the abscissa indicate the forecast time the quadrants that were forecast for each forecast interval.

Overall, as the JTWC forecast track error increase, so do the TYDET forecast wind speeds. For example, the forecast track error for one of the 36-hour forecasts in the right-rear case was 153 n mi and this produced a -25 knot TYDET wind speed error. Not all track errors will lead to large TYDET errors, because some track errors will offset the biases in the TYDET model. Indeed, the track errors may also offset some of the biases that are hypothesized to be due to the lack of size and symmetry information in the TYDET model.

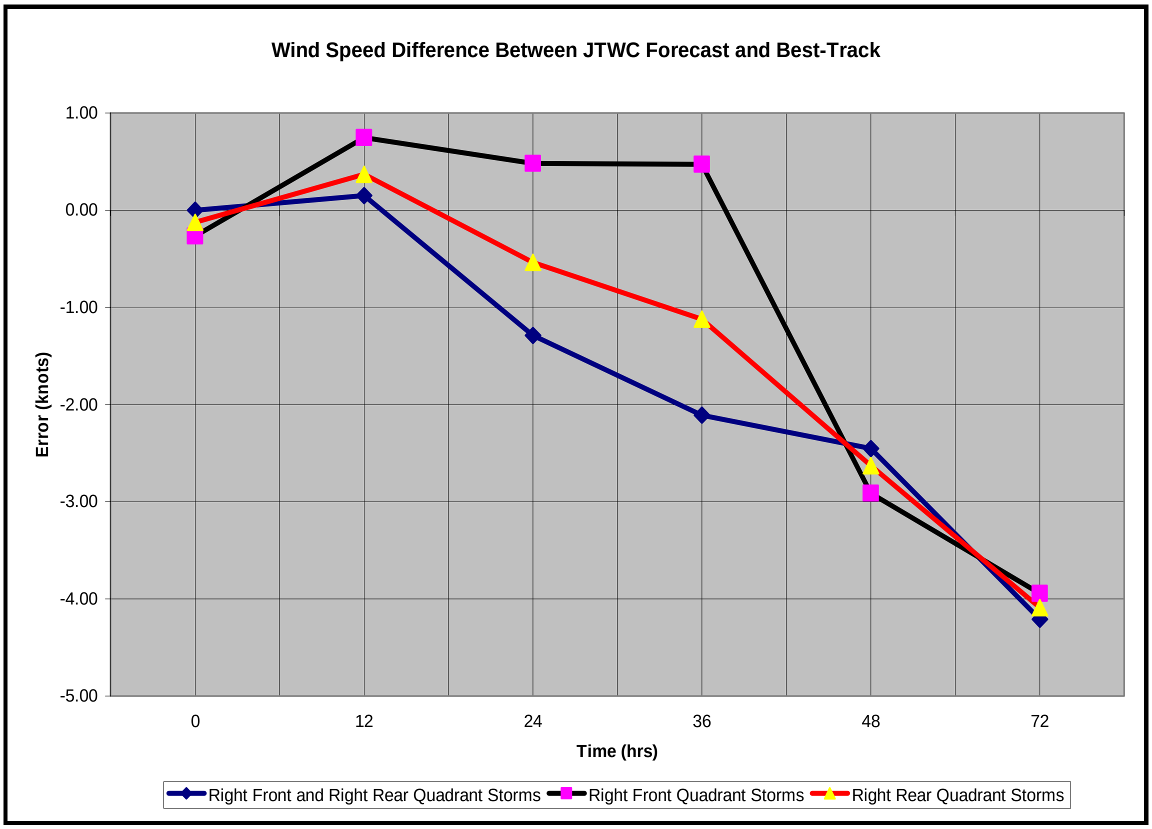


Figure 41. Speed difference in TYDET between using JTWC forecast versus using the best-track data by time interval for the combined set of storms in which Okinawa was in the right-front and right-rear quadrants (blue), or subsets of storms in the right-front quadrant (black) and the right-rear quadrant (red).

### 2. Errors in TC Size

Another source of error in the JTWC forecast data used as input to TYDET is that of the forecast 34-knot wind radii in each quadrant. If the 34-knot wind radii are erroneously forecast, than the size of the storm as defined here will be incorrect. The average JTWC forecast under-forecasts the TC size for all time intervals (Figure 42). This size error would have no effect on the current TYDET program that does not take into account the storm size. The typical size error in the forecast data must be identified to determine the potential effect on a corrected TYDET forecast that would include size. Since the best-track data were used to explain the contributions of size in the TYDET errors, it is assumed that the larger the JTWC size forecast errors, the larger the TYDET speed errors.

Errors in the 34-knot radii forecasts increase as the forecast time interval increases, but then level out after 48 hours when Okinawa is in the right-front quadrant of the storm (Figure 43). Perhaps due to the reduced number of cases at 72 hours, the 72-hour forecast radii error actually decreases in these right-front quadrant case. Much more variability exists in the forecasts of 34-knot wind radii for TCs in which Kadena AB is in the right-rear quadrant (Figure 44). In particular, the errors in the southwest and northwest quadrants are close to zero rather than strongly negative as are the errors to the northeast and southeast quadrant. This is due to the variability associated with the smaller sample size of right-rear cases and to the tendency for the JTWC forecast size to increase following recurvature.

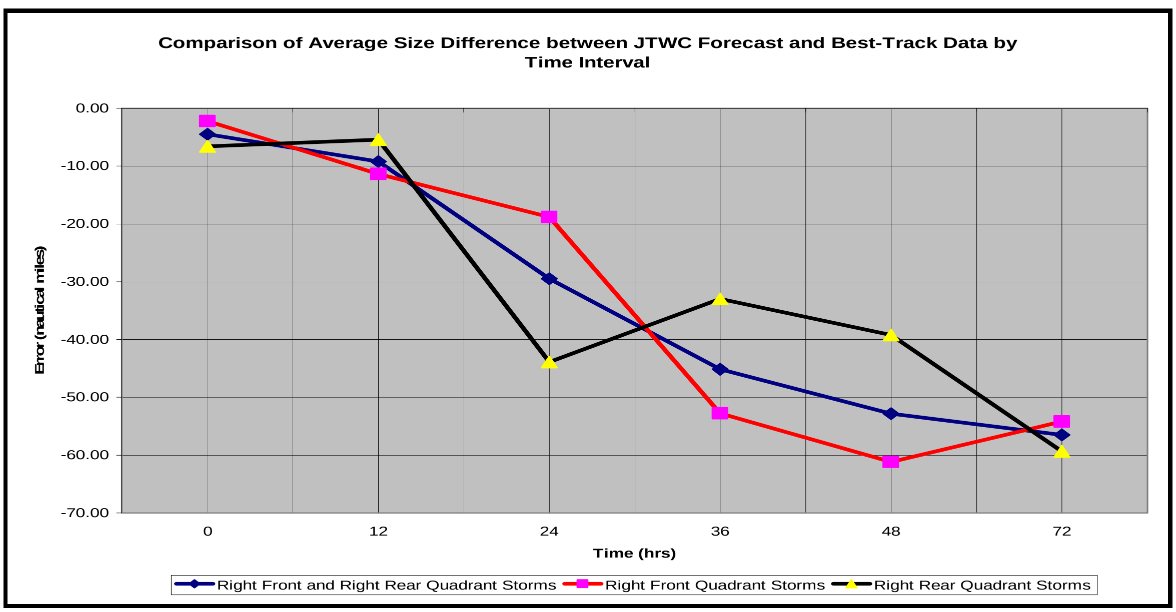


Figure 42. Forecast errors (n mi) in storm size determined using the JTWC best-track size values.

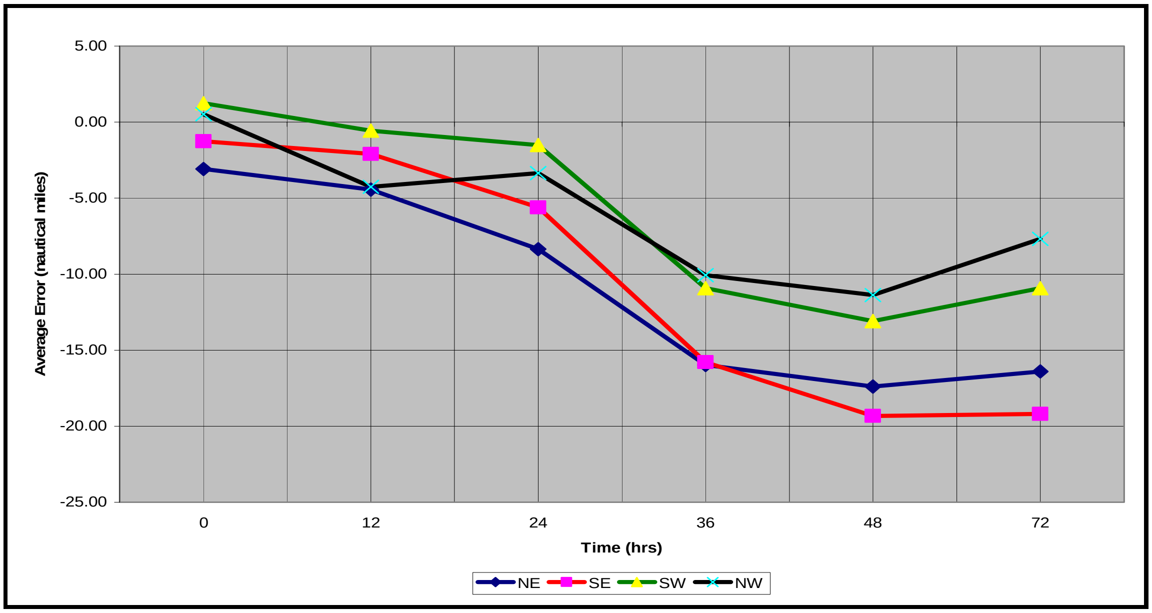


Figure 43. Average error (n mi) in JTWC forecast of storm radius when compared with JTWC best-track quadrant radii for each given forecast time. These errors are for storms in which the right-front quadrant was affecting Kadena AB. The four different JTWC quadrants are represented. The NE (blue), SE (red), SW (green), and NW (black).

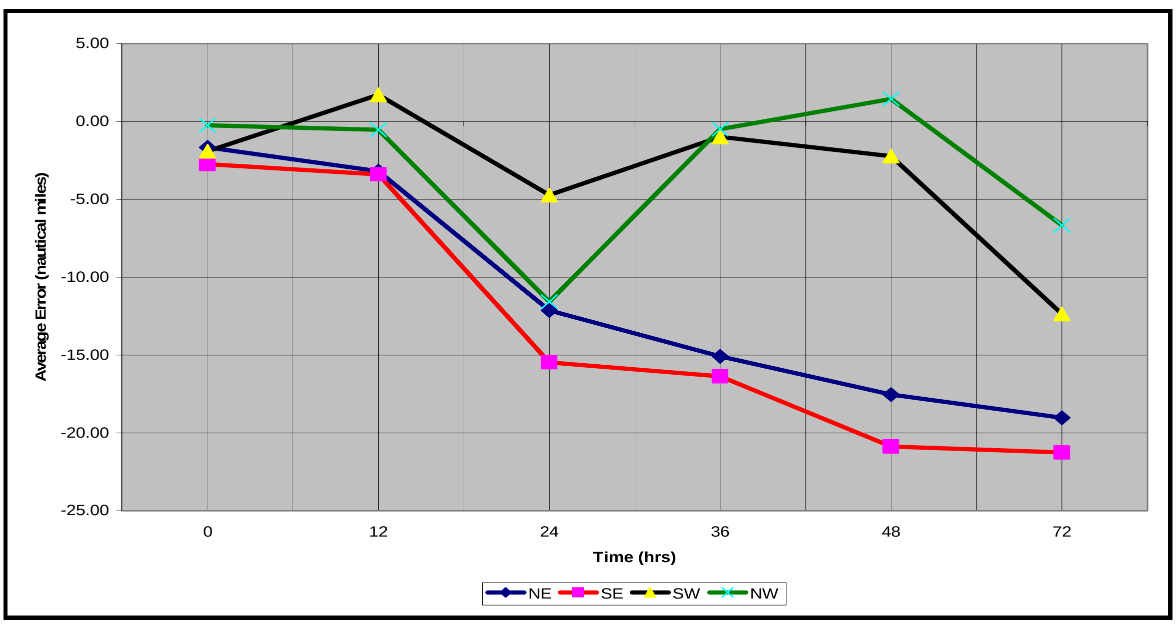


Figure 44. Average error (n mi) in JTWC forecast of storm radius when compared with JTWC best-track quadrant radii for each given forecast time. These errors are for storms in which the right-rear quadrant was affecting Kadena AB. The four different JTWC quadrants are represented. The NE (blue), SE (red), SW (green), and NW (black).

It is important to not only examine the size forecast errors, but also to examine the statistical relevance of the size when compared with other relevant parameters such as wind speed and range. An inverse linear relationship exists between the TYDET forecast speed error and the range error in the JTWC forecast (Figure 45). While the 48-hour forecast interval (Figure 45) is used as an example, this relationship existed at all forecast time intervals. When there is a positive range error (storm is forecast to be too far away), the TYDET wind speed is under-forecast. Some indication exists that if the range is too large and the size is too small, the TYDET wind speed errors will be more negative. Generally, when the storm is too close, the wind speed is over-forecast. Notice that when the range errors are categorized by storm size in Figure 45, the dependence of TYDET wind speed forecast on range error dominates the dependence on size error.

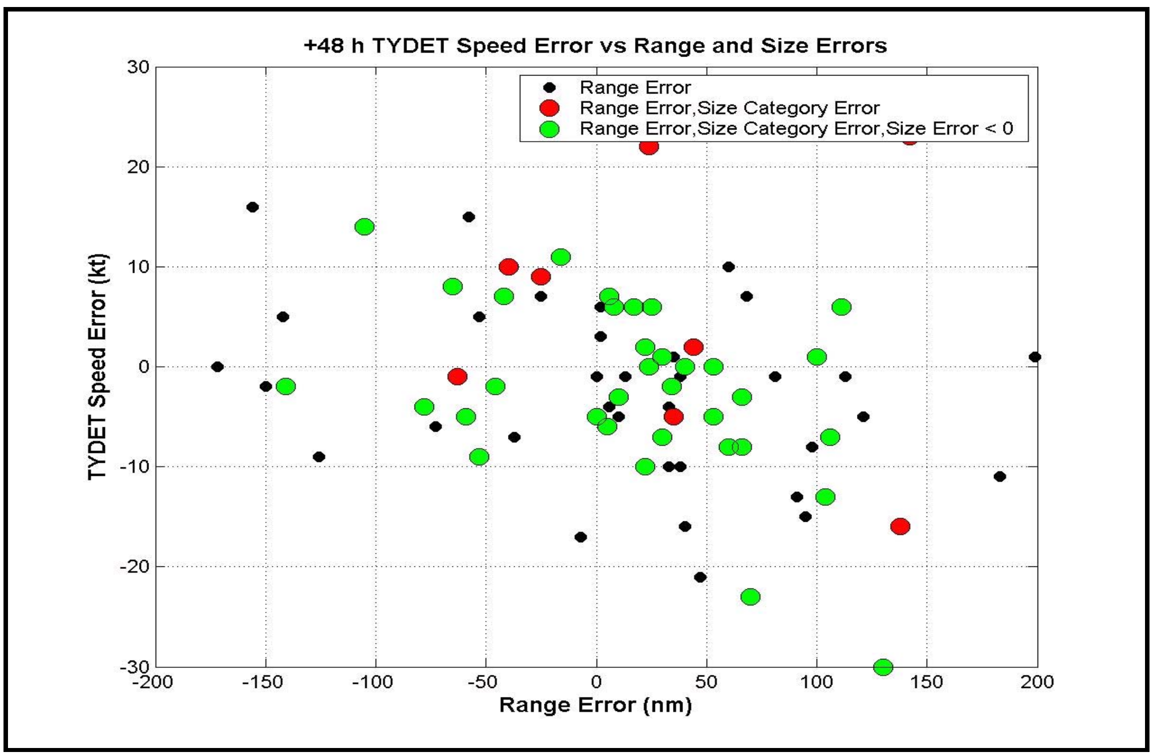


Figure 45. The TYDET wind speed error (kt) versus JTWC forecast range error (n mi). The individual values are plotted for a correct size category forecast (black dot), incorrect size category forecast such that the size forecast was too small (green dot), and a too large size forecast (red dot). All forecasts compare the TYDET forecast using the JTWC forecast and the TYDET forecast using JTWC best-track data.

In summary, this section has examined the errors in TYDET based upon the lack of size information in the model. The conclusion is that not only will the size information need to be added to the TYDET model, but a correction will also be required to account for the range error in the JTWC track forecast. Without incorporating the JTWC track forecast error, only about half of the error would be accounted for and less improvement would be shown.

### 3. Forecast Asymmetry Errors and Statistical Relevance

Finally, the asymmetry errors due to the JTWC forecast were examined. Asymmetry errors for the combined storm group became more negative as the forecast time period increased (Figure 46). These asymmetry errors have some of the same patterns as the size errors, which may be expected since both relied on the 34-knot radii forecasts and would therefore be subjected to many of the same errors. In the combined storms group, the asymmetry errors do not continue to increase in the 36- to 72-hour forecast intervals. The asymmetry errors in right-front and right-rear quadrant groups are consistent with the overall group in that the errors increase steadily and then become constant or decrease at 48 hours (Figure 46). These asymmetry errors may cause a TC to be mis-classified as symmetric (<30 nautical miles) or asymmetric (>= 30 nautical miles), which may have a large effect on whether or not the storm will influence Kadena AB.

Another factor that makes the asymmetry forecast prone to error is the wind radius error in each storm quadrant as forecast by JTWC. This was addressed with respect to size errors, but is also relevant to asymmetry errors. For example, if the 34-knot wind radius in the northwest quadrant is under-forecast and the radius in the southeast quadrant is over-forecast, the asymmetry parameter will not be calculated correctly and the asymmetry will not be properly classified. This scenario can also be the difference between being correct or incorrect in forecasting whether a storm will affect Kadena AB. The asymmetry errors are compounded when the JTWC forecasts are used as input instead of the best-track data.

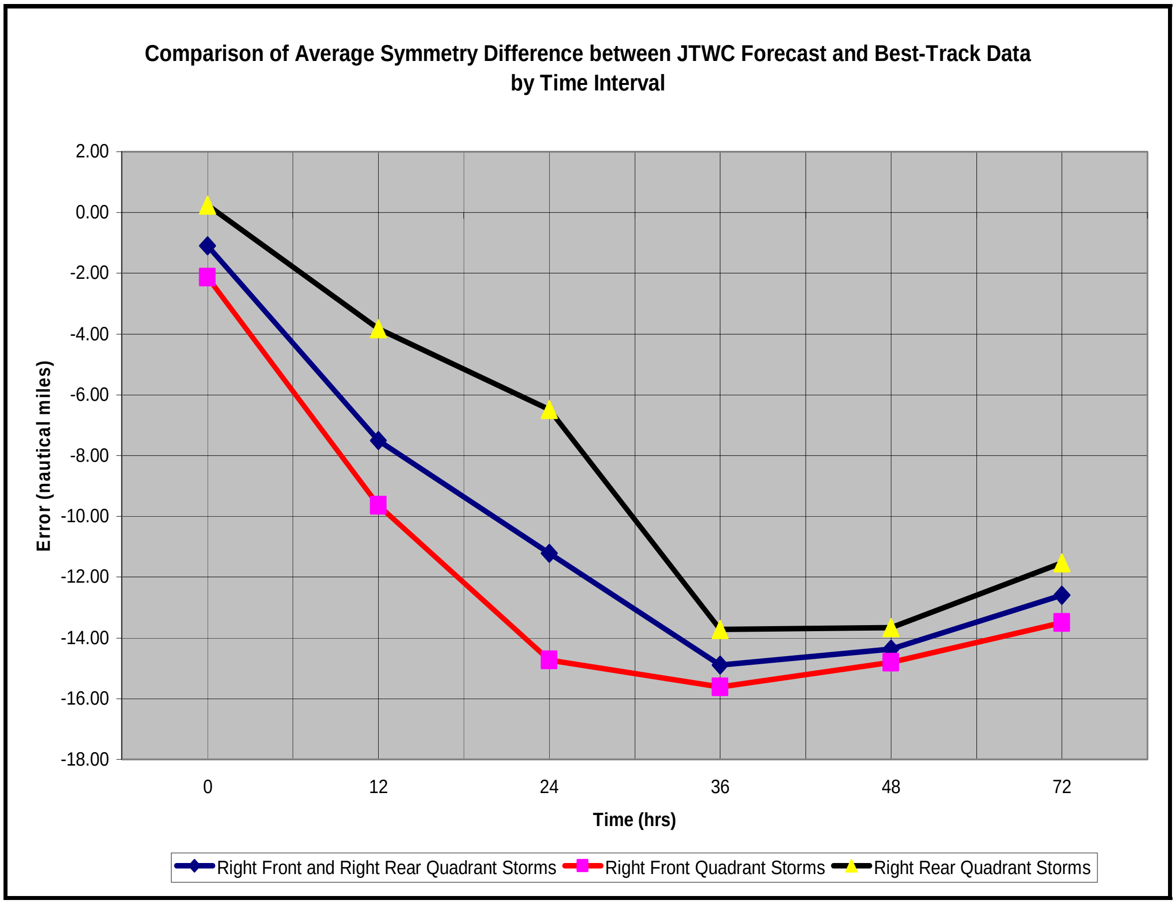


Figure 46. Average error in JTWC forecast asymmetry parameter when compared with best-track symmetry parameter for each given forecast time. These errors are for storms in which the right-front and right-rear quadrant combined (blue), right-front quadrant (red), and the right-rear quadrant (black) affected Kadena AB.

Again, relative contribution to the TYDET wind errors from the asymmetry errors versus range errors must be examined. These TYDET speed errors at 48 hours have an inverse relationship (Figure 47) between the range error and the asymmetry error. A similar relationship existed through all of the forecast intervals. Notice some indication that a forecast that places the TC too close to Kadena AB and predicts the TC to be too symmetric is associated with the largest TYDET over-forecast errors.

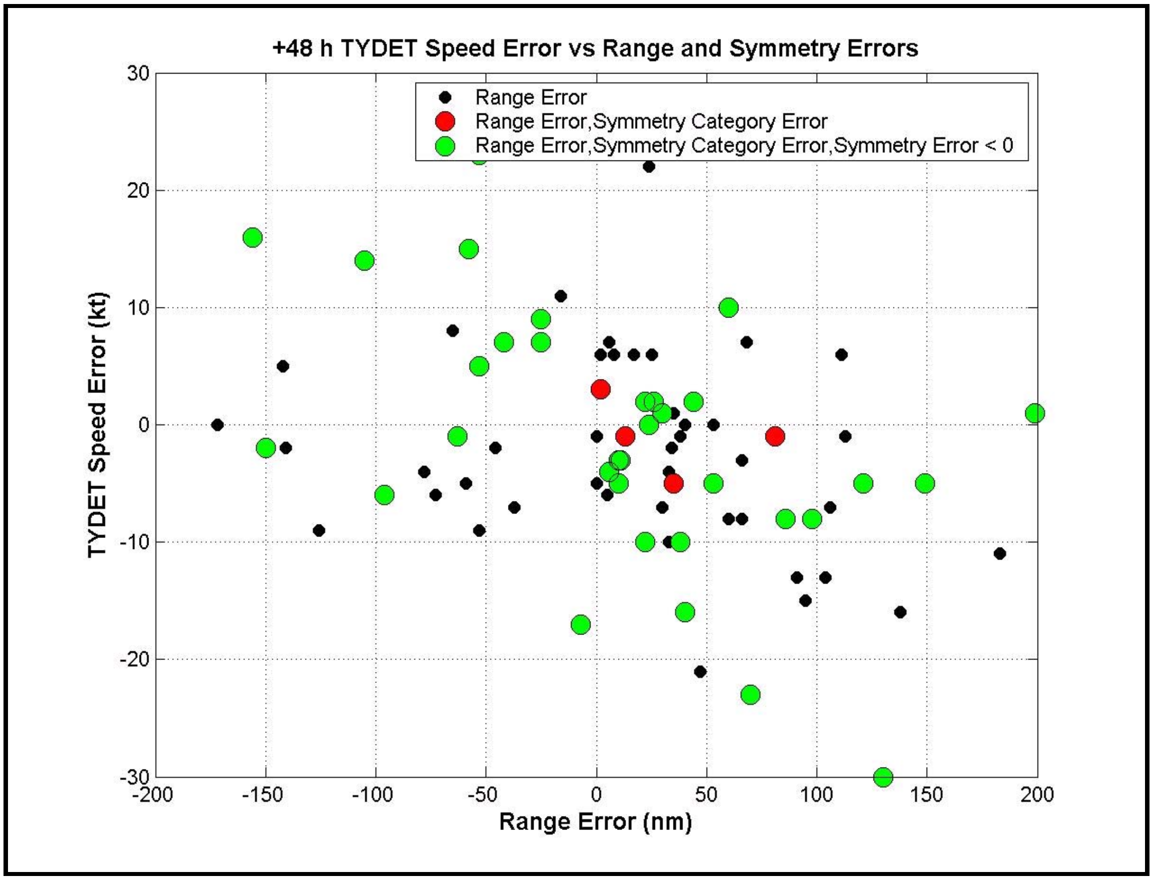


Figure 47. As in Figure 45, except for asymmetry errors. Here the 48-h TYDET speed errors associated with an asymmetry forecast in the correct category with only range error are plotted as a black dot, asymmetry forecasts that were too symmetric are plotted as a green dot, and forecasts that are too asymmetric are plotted as a red dot. All forecasts compare the TYDET forecast using the JTWC forecast and the TYDET forecast using JTWC best-track data.

## C. REGRESSION-BASED CORRECTIONS

An objective of this research was to examine the errors inherent to the TYDET model and then attempt to improve the forecast by applying a correction based on these systematic errors. To improve the TYDET forecast by incorporating the size and asymmetry factors, a series of linear regressions were developed to determine forecast correction coefficients to adjust the TYDET forecast. Three different linear regressions were developed: (i) a regression for wind speed only; (ii) a regression for the wind u-component; and (iii) a regression for the wind v-component. The speed regression provides an updated wind speed forecast, and the u- and v-component regressions provide updated u- and v-components that were then converted to updated speed and direction forecasts.

Although the regression procedure will only be discussed here with respect to the speed-only regression, the u- and v-component regressions were also developed in a similar manner. The linear regression consisted of a two-part process. The first step was to run a stepwise linear regression to determine which dependent variables were statistically relevant (Table 1) and their corresponding regression coefficients. The predictors that were examined included the original TYDET wind speed forecast, JTWC forecast size, JTWC forecast maximum sustained wind, JTWC forecast asymmetry, JTWC forecast range from Kadena AB to the storm center, JTWC forecast heading from the storm toward Kadena AB, and JTWC forecast bearing. The p-value that was used to determine whether a predictor would be entered in the regression was 0.15. Notice the most frequently and therefore most statistically relevant variables were the TYDET wind speed forecast, the JTWC forecast size, and the JTWC forecast range from Kadena AB to the storm center. This agrees with the assertions that were made in previous sections regarding the significance of size and range. The JTWC forecast asymmetry was not selected as a predictor as much as expected, but when it was selected, it often was selected with only one other predictor or by itself. The regression was then utilized to calculate a predicted wind speed error that is to be used to adjust the original TYDET forecast. Again, the goal of the adjusted forecast is to improve the original TYDET forecast by bringing it closer to the observed wind conditions at Kadena AB.

The linear regression procedures were run using both the JTWC best-track data and the JTWC forecasts as the inputs to TYDET. Once the regressions were run, the adjusted wind speeds were analyzed to see if they had been improved or had been degraded by the procedure. Using the adjusted speed and adjusted speed and direction from the regressions on u and v components, the cross-wind was calculated. These results will be described in the following subsections.

The adjusted values were plotted to examine the predicted wind speed error using the dependent data (Figure 48). The adjusted wind speed errors (green dots, Figure 48) are reduced in the majority of cases when compared to the original TYDET wind speed errors (black dots, Figure 48). Notice the large speed errors for a number of cases in the original TYDET wind speed forecast at the 48-hour JTWC forecast interval (Figure 48). Cases 15 and 23 display original TYDET wind speed errors or -30 and -23 knots, respectively. The adjusted forecast wind speed error for both these cases is -8 knots. The regression was very successful in correcting the largest original TYDET forecast wind speed errors.

Improvement is seen in the 48-hour adjusted wind speed forecast when it is examined against the original TYDET wind speed forecast and the observed wind speed at Kadena AB (Figure 49) for the majority of the wind speed forecasts. The 48-hour forecast is examined to observe the improvement or degradation in the forecast wind speed when the speed regression is run. The adjusted wind speed forecasts (green dots, Figure 49) move closer to the observed wind speeds (red dots, Figure 49) than the original TYDET wind speed forecasts (black dots, Figure 49) in the majority of the cases. Again, this is particularly true for times when the original TYDET wind speed errors are the largest. Case 66 in Figure 49 illustrates the dramatic improvement that was made for many of the cases. The original TYDET wind speed forecast was for 53 knots and the observed wind speed forecast was for 30 knots. After the regression was run, the adjusted wind was 31 knots. There were similar improvements made for other cases at the 48-hour forecast interval and other forecast intervals. Notice the overall improvement in the root mean square error (RMSE). For the 48-hour JTWC forecast interval the RMSE went from 10.31 to 7.19.

After the regression results are examined based on the dependent data set, a jackknife procedure (Wilks 2006) is used to evaluate the regression equation based on independent data (Figure 50). The jackknife procedure removes one case and then re-derives a regression model that is used to predict the speed error for the omitted case. An adjusted speed forecast is then produced for the omitted case. This method of testing the adjusted TYDET model was necessary due to the small number of cases that were available for study. The jackknife adjusted wind speed forecast should be between the original TYDET wind speed forecast and the dependent sample regression forecast. Therefore the RMSE of the adjusted wind speed forecast when the independent data is used will be higher than the RMSE of the adjusted wind speed forecast when the dependent data is used. Notice the adjusted wind speed forecast RMSE is 7.19 in Figure 49 (dependent data) and 7.95 in Figure 50 (independent data).

| Regression | Quadrant | Time | Predictor | Coefficient |
|---|---|---|---|---|
| Speed Only | Right-Front | Best-Track | 1,3,5 | .5640,-.0999,.0455 |
| Speed Only | Right-Front | 0 | 1,2,3,5,7 | .4994,-.0272,.076,.043,.0356 |
| Speed Only | Right-Front | 12 | 1,2,5 | .9099,-.0283,.0484 |
| Speed Only | Right-Front | 24 | 1,2,5 | .5593,-.0190,.0187 |
| Speed Only | Right-Front | 36 | 1,2,3 | .6048,-.0290,.0573 |
| Speed Only | Right-Front | 48 | 1,2,4,5,7 | .4859,-.00095,.154,.0221,.0407 |
| Speed Only | Right-Front | 72 | 1,3 | .6558,-.0803 |
| Speed Only | Right-Rear | Best-Track | 1,3,5,6 | .5092,-.1095,.0398,.0045 |
| Speed Only | Right-Rear | 0 | 1,2,3 | .5722,-.0243,.0457 |
| Speed Only | Right-Rear | 12 | 1,2 | .4702,-.0266 |
| Speed Only | Right-Rear | 24 | 1,2,5 | .7143,-.0192,.0345 |
| Speed Only | Right-Rear | 36 | 1,2,3 | .7966,-.0248,-.0818 |
| Speed Only | Right-Rear | 48 | 1,2,4,5 | .5757,-.0208,-.2507,.0312 |
| Speed Only | Right-Rear | 72 | 1,2,6 | .8202,-.0263,-.0220 |
| u-component | Right-Front | Best-Track | 1,3,5 | -.4311,.1368,-.0231 |
| u-component | Right-Front | 0 | 1,2,3,4,5 | -.8781,.0213,.0557,.0707,-.0385 |
| u-component | Right-Front | 12 | 1,6,7 | -.5664,.0141,.0266 |
| u-component | Right-Front | 24 | 1,3,5 | -.7367,.1679,.0312 |
| u-component | Right-Front | 36 | 1,3,4 | -.8543,.1379,-.3483 |
| u-component | Right-Front | 48 | 1,3 | -.3746,.0567 |
| u-component | Right-Front | 72 | 1 | -.6575 |
| u-component | Right-Rear | Best-Track | 1,4,6 | -.0760,-.0540,.0075 |
| u-component | Right-Rear | 0 | 1,4 | -.2725,.0920 |
| u-component | Right-Rear | 12 | 4 | .1629 |
| u-component | Right-Rear | 24 | 2 | -.0262 |
| u-component | Right-Rear | 36 | 1,2,6 | -.3819,.0203,-.0261 |
| u-component | Right-Rear | 48 | 1,3 | -.5646,.2072 |
| u-component | Right-Rear | 72 | 4,6 | -.4464,-.0276 |
| v-component | Right-Front | Best-Track | 1,5 | .2468,.0369 |
| v-component | Right-Front | 0 | 1 | -.3366 |
| v-component | Right-Front | 12 | 1,3,6 | .4886,-.1185,.0193 |
| v-component | Right-Front | 24 | 1,4 | .5630,-.1932 |
| v-component | Right-Front | 36 | 2 | 0.0258 |
| v-component | Right-Front | 48 | 1,4 | .3464,-.2572 |
| v-component | Right-Front | 72 | 1,7 | .3047,.0576 |
| v-component | Right-Rear | Best-Track | 1,3,5,6,7 | .1585,-.1072,.0415,.0108,.0128 |
| v-component | Right-Rear | 0 | 1,2,6 | .4104,-.0094,.0123 |
| v-component | Right-Rear | 12 | 2 | -.0339 |
| v-component | Right-Rear | 24 | 1,2,7 | .3518,-.0394,-.0327 |
| v-component | Right-Rear | 36 | 1,3,6 | .2126,-.2561,.0544 |
| v-component | Right-Rear | 48 | 1,5 | .4389,.0719 |
| v-component | Right-Rear | 72 | 1,2,4,6 | .6288,-.0286,.1434,-.0522 |

**Predictors:**
**1=Original TYDET Wind-Speed Forecast**
**2=JTWC Forecast Size**
**3=JTWC Forecast Sustained Wind**
**4=JTWC Forecast Symmetry**
**5=JTWC Forecast Range**
**6=JWTC Forecast Heading**
**7=JTWC Forecast Bearing**

Table 1. The regression predictors (fourth column, see definitions at bottom) and their coefficients (fifth column) that were selected for each of the regressions listed in the left column. Either right-front or right-rear quadrant (second column) data sets are used for JTWC best-track or various forecast intervals (third column).

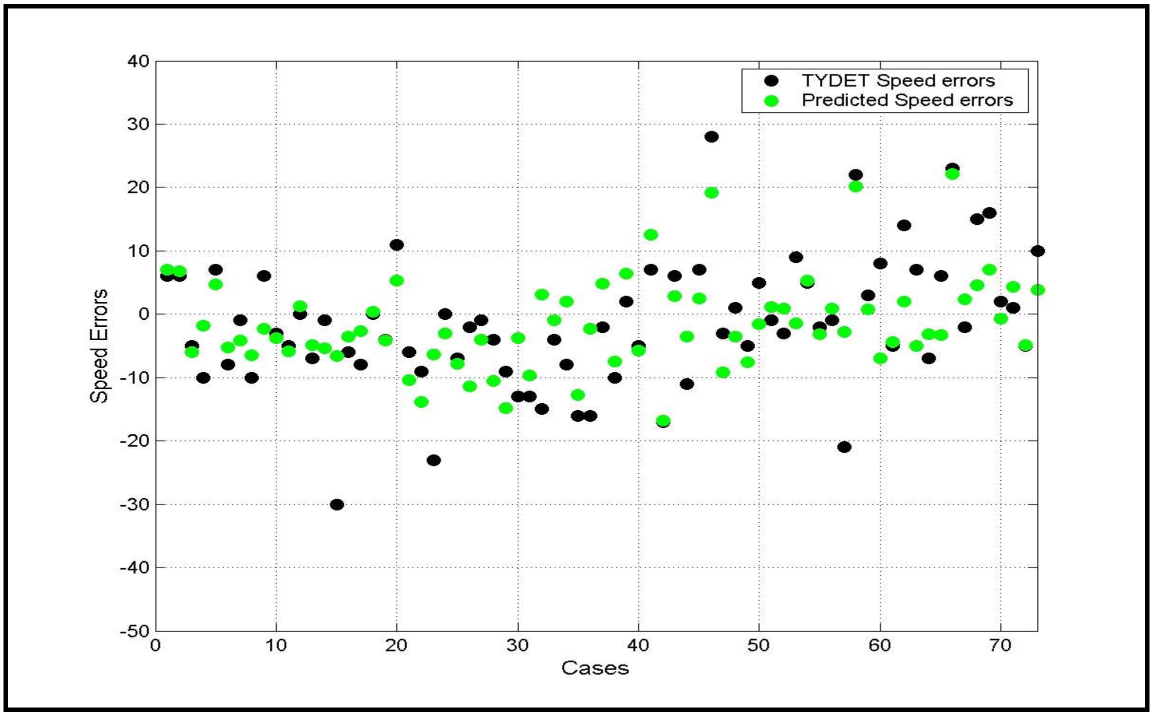


Figure 48. The original 48-h TYDET speed errors (kt) (black) and the speed errors (kt) predicted by the linear regression (green) procedure for all TC cases in which Kadena AB was in the right-front quadrant.

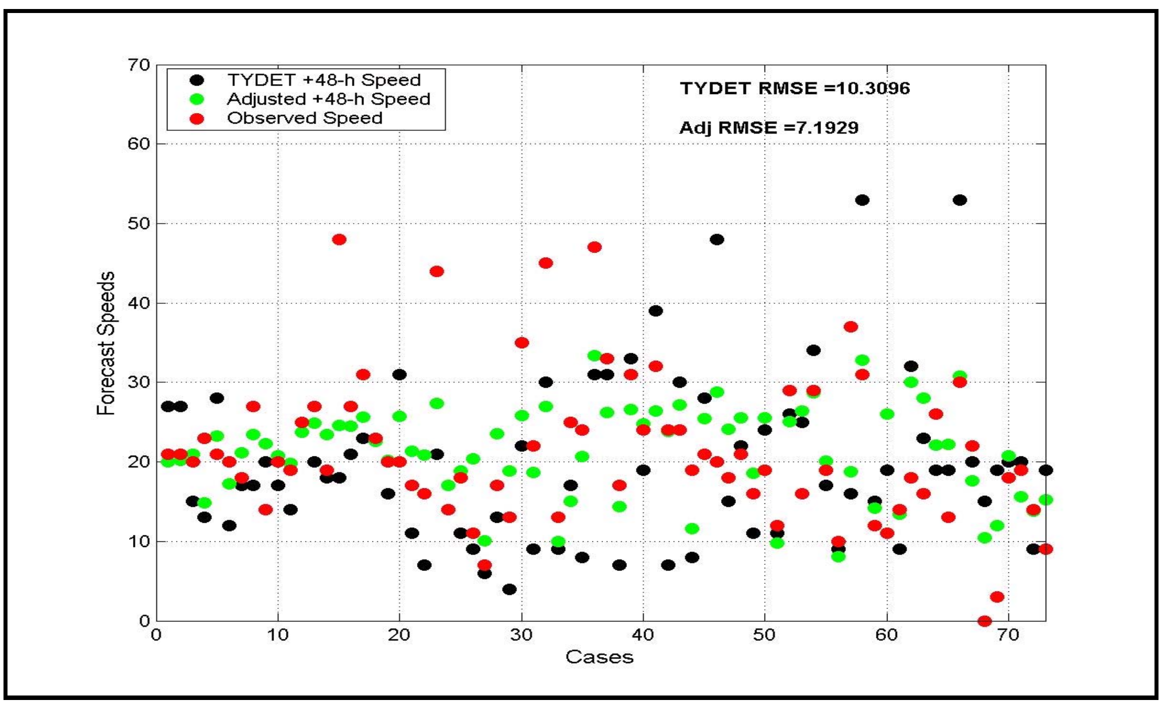


Figure 49. The original 48-h TYDET forecast wind speed (kt) (black), the observed wind speed (kt) (red) and the (adjusted) wind speed forecast (kt) (green) derived from the regression based on the dependent data.

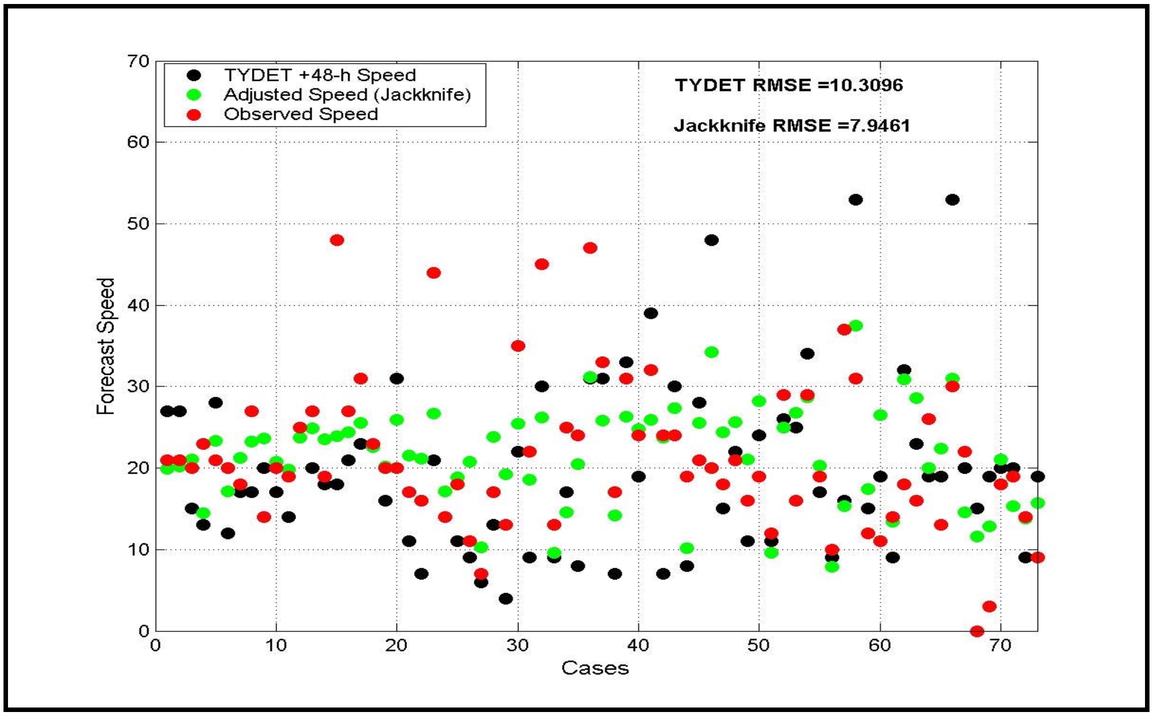


Figure 50. The original 48-h TYDET forecast wind speed (kt) (black), the observed wind speed (kt) (red) and the adjusted wind speed forecast (kt) (green) based on the jackknife procedure.

### 1. Evaluation of Wind Speed Adjustments Using Best-Track Data

There are many ways that the size and asymmetry could be added to the TYDET program, but not all would improve the program significantly. The RMSEs of the original TYDET calculations, the adjusted values, and then the RMSE of the jackknife adjusted forecasts is a quantitative metric for this evaluation (Figure 51). Notice the lower RMSE for the adjusted wind speed forecast using the dependent data and for the jackknife adjusted wind speed forecast when compared to the RMSE for the original TYDET forecast. The right-rear case shows very similar improvements (Figure 55) with just slightly higher RMSE. The wind-speed RMSE for both the speed only regression and the u-v-component regression show considerable improvement. In both cases the RMSE are reduced by almost half. The best-track cases should produce quality results because the data input into the linear regression is essentially a perfect forecast. It is interesting to note that the RMSE of the original TYDET forecast is quite large. Therefore, the adjustments made to the best-track data are adjustments made to the systematic error within TYDET.

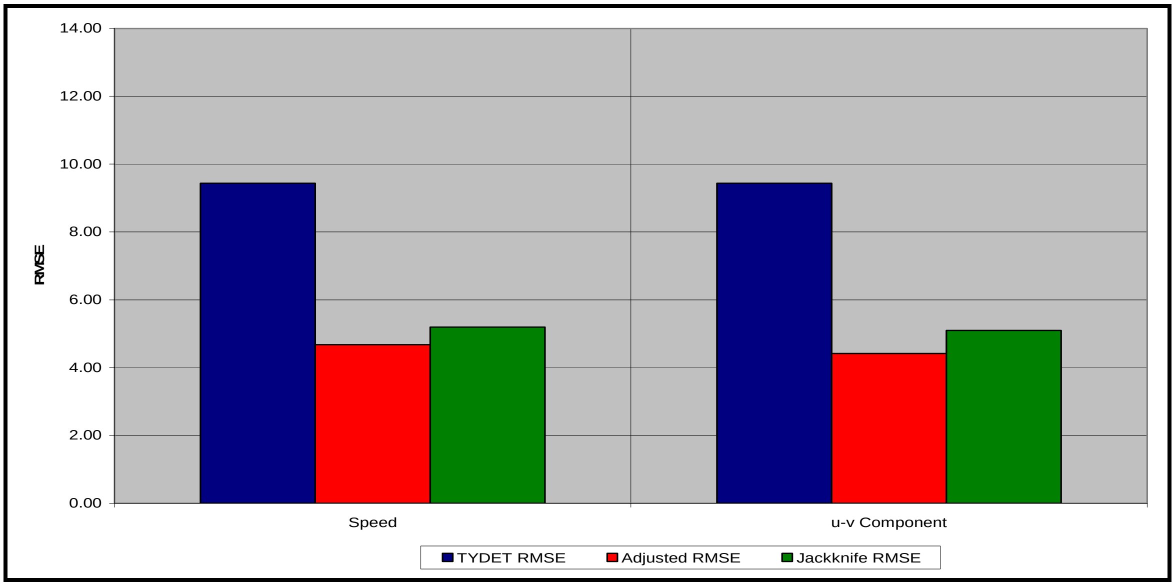


Figure 51. Wind speed RMSE (kt) for the original TYDET forecast (blue), forecast adjusted using dependent data (red) and the forecast adjusted using independent data (green) for storms in which Kadena AB is in the right-front quadrant when best-track values are used for deriving the regressions and the jackknife evaluation.

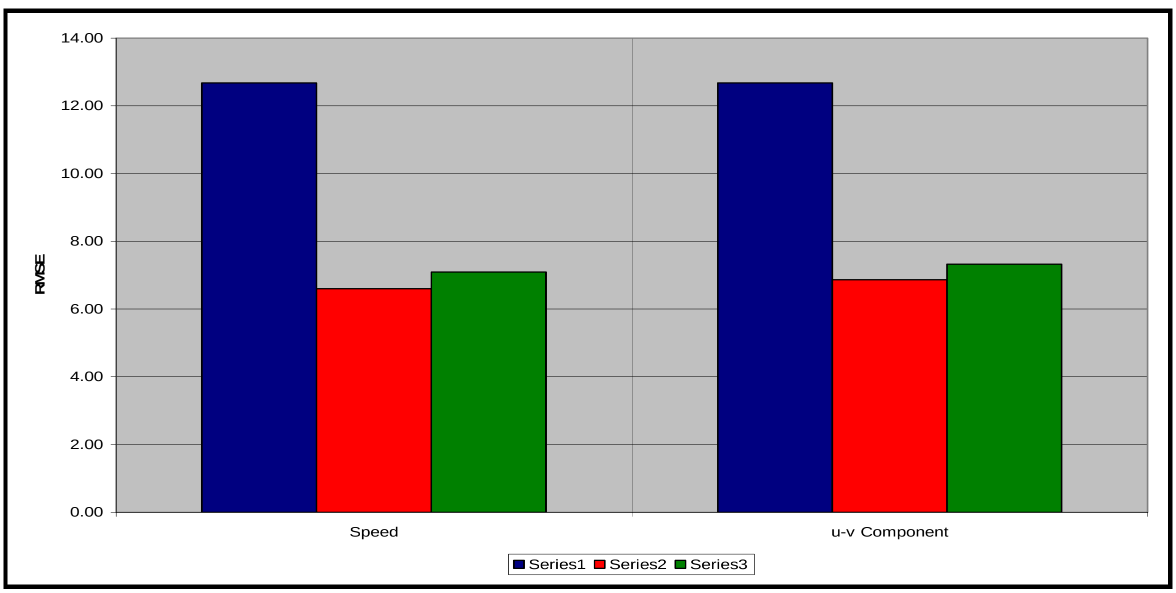


Figure 52. As in Figure 51, except for storms in which Kadena AB is in the right-rear quadrant.

### 2. Evaluations of Wind Speed Adjustments Using JTWC Forecasts

The regressions were also developed and evaluated for the TYDET model using the 0-, 12-, 24-, 36-, 48- and 72-hour JTWC forecast values as inputs. The adjusted wind speed forecast for the regression based on the dependent data, and the jackknife-derived wind speed forecast had RMSE values that were reduced compared to the original TYDET forecast RMSE for all forecast intervals when Kadena AB was in the right-front quadrant (Figure 53). The corresponding RMSE values for the regressions developed from best-track data are displayed on the same chart to provide a baseline for the regressions based on JTWC forecast values. The regression results when Kadena AB was in the right-rear quadrant (Figure 54) display slightly more variability in RMSE values than when Kadena AB is in the right-front quadrant while still being an improvement over the original TYDET forecast.

The original TYDET wind speed and direction were converted to u- and v-components. The u- and v-component regressions were run to adjust for both speed and direction errors. The u-component and the v-component were run through separate regressions and the adjusted values were then converted back to wind and speed forecasts. The u- and v-component regressions for storms when Kadena AB is in the right-front and right-rear quadrants (Figure 55 and 56) were not always an improvement over the original TYDET forecast. The RMSEs when Kadena AB is in the right-front quadrant are variable and at the 36-hour forecast interval the RMSE for the adjusted forecast using independent data is worse than the original TYDET forecast RMSE (Figure 55). When the right-rear quadrant affects Kadena AB the RMSE of the adjusted wind speed forecast at the 12- and 48-hour forecast intervals is also worse than the RMSE of the original TYDET wind speed forecast (Figure 56). Therefore, the u- and v-component regressions are not as effective as the speed only regressions.

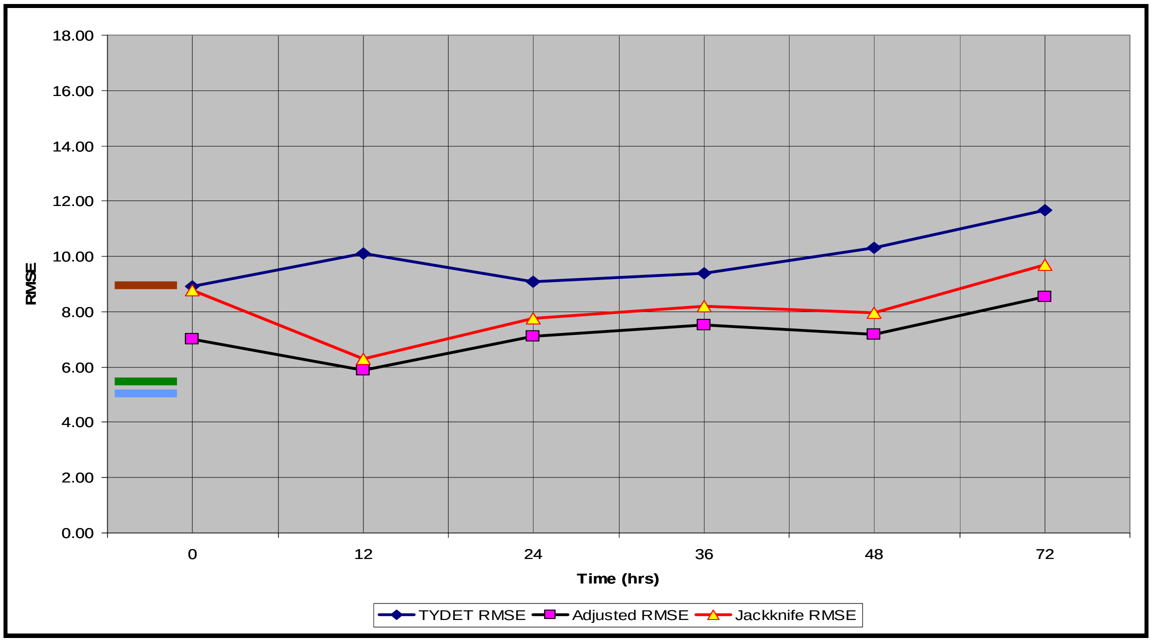


Figure 53. Speed RMSE (kt) for the original TYDET winds (blue), adjusted winds (black)), and the jackknife winds (red) based on the speed regression for the storms in which Kadena AB is in the right-front quadrant. The values for the time 0 h that are derived from best-track values are shown to the left as a baseline for these results of regressions based on JTWC forecasts at the times (h) shown.

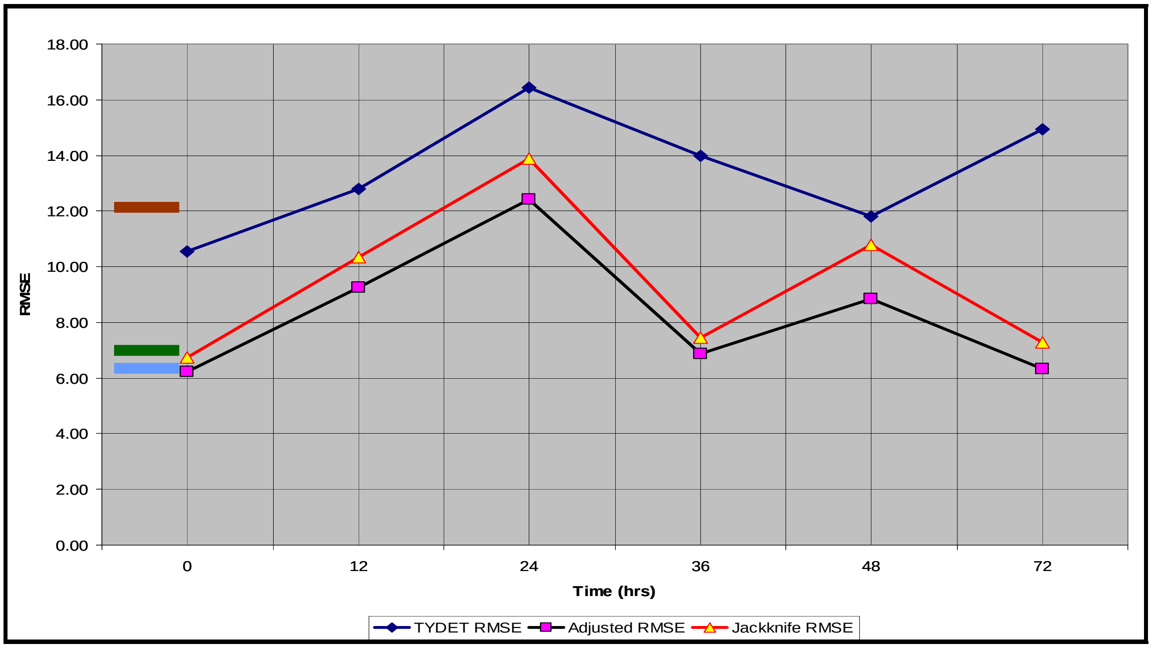


Figure 54. As in Figure 53, except for storms in which Kadena AB is in the right-rear quadrant.

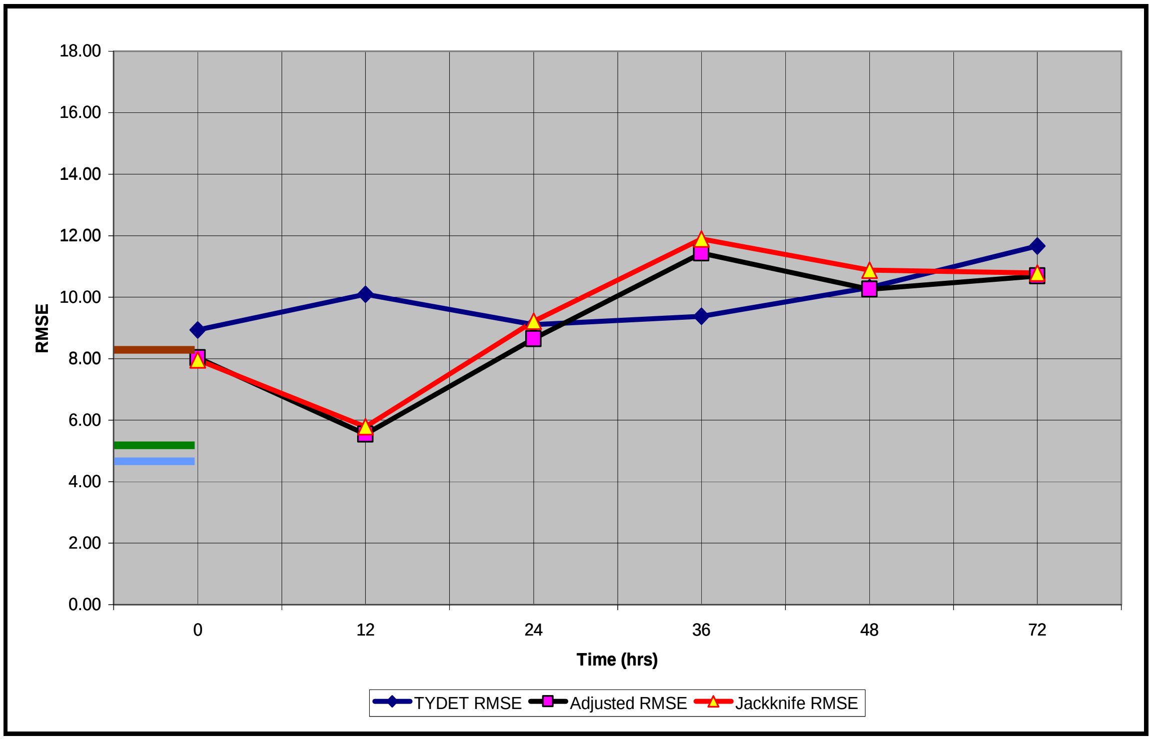


Figure 55. Speed RMSE (kt) as in Figure 56, except based on the u,v-component regression for storms in which Kadena AB is in the right-front quadrant.

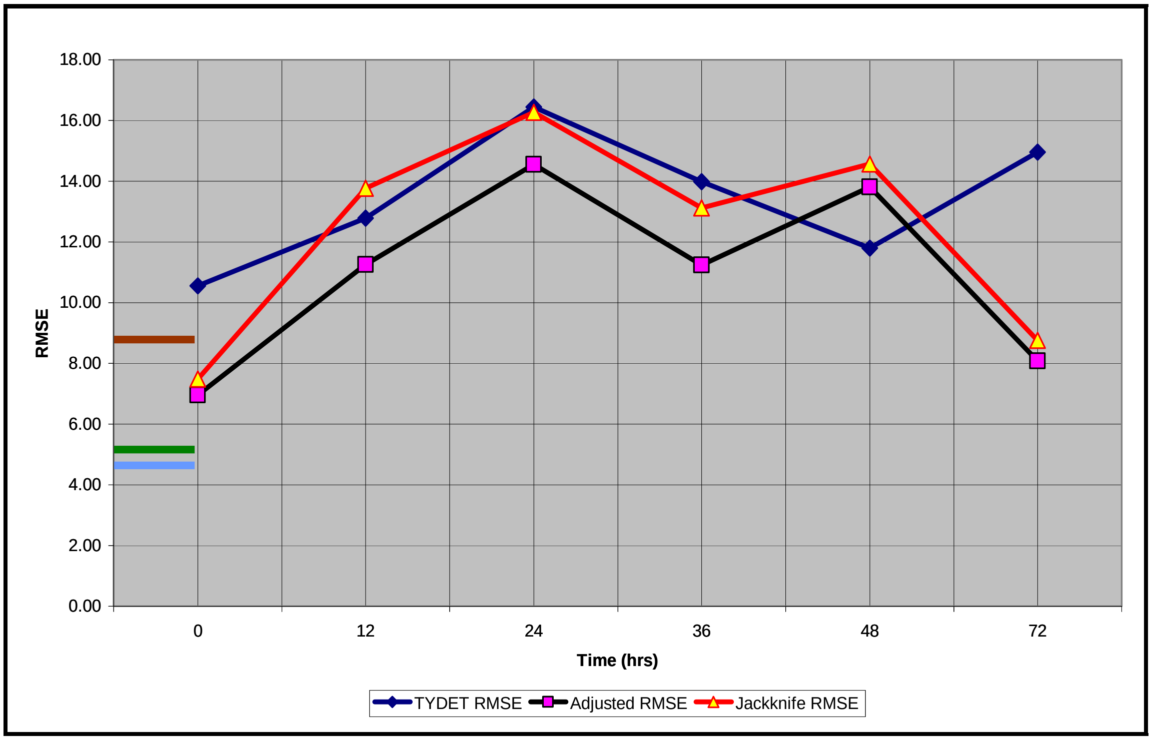


Figure 56. As in Figure 55, except for storms in which Kadena AB is in the right-rear quadrant.

### 3. Cross-Wind Improvements Using Best-Track Product

The runway cross-wind forecast, which is the most essential product of TYDET, was calculated using the corrected speed forecast from the speed regression and the corrected speed and direction forecasts from the u- and v-component regressions for the best-track data to create a baseline for improvement. This cross-wind takes into account not only the wind speed but also the wind direction relative to the orientation (230 degrees) of the runway at Kadena AB. Although the direction derived from the u- and v-component regressions or the adjusted speed forecast may be degraded, it is possible the cross-wind could actually be improved if the direction error offset a speed error or vice versa. For example, a 16 knot wind with a wind direction of 140 degrees and a 25 knot wind with a wind direction of 270 degrees both have a cross-wind of 16 knots. These varying combinations with the runway orientation can make the determination of whether or not the adjusted forecasts are actually improved somewhat confusing.

The RMSE for the cross-wind forecasts using the adjusted wind speed forecasts and the directions from adjusted wind speed forecasts from the u- and v-component regressions for storms in which Kadena AB is in the right-front quadrant (Figure 57) and the right-rear quadrant (Figure 58) do indeed show improvements when the best-track data are used. The cross-wind calculations using the u- and v-regression speed values show less improvement, but still show improvement over the original TYDET forecast.

Another indication of the improvement in cross-wind forecasts would be that the number of cases that are improved is much larger than those degraded. The number of improved cases was almost twice the number of cases that were degraded (Figure 59). An additional measure of improvement was how much the cross-wind forecast was improved or degraded when the observed cross-wind was in excess of certain critical levels. Since some aircraft have a 15 or 20 knot maximum cross-wind with a wet runway, the number of times the cross-wind forecast was improved when these critical levels were observed was calculated for the combined sample of storms in which Kadena AB was in the right-front and right-rear quadrants (Figure 60). Again, the improved forecasts out-numbered degraded forecasts regardless of whether the adjusted speed and direction or just the adjusted speed was used to improve the TYDET forecast. In the case of the 15 knot critical level, the ratio of improved to degraded cross-wind forecasts is about 3:1.

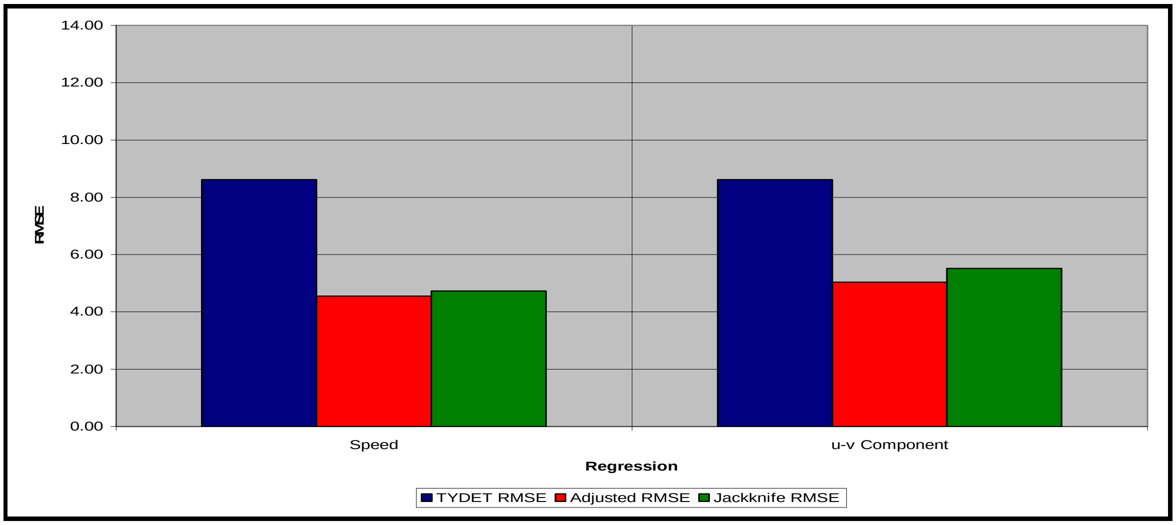


Figure 57. Cross-wind forecast RMSE (kt) for the original TYDET forecast (blue), for the adjustments based on dependent data (red) and for the jackknife adjustments (green). The left plot exhibits the RMSE from the speed-only regression and the right exhibits the RMSE for the u- and v-component regressions for TYDET forecasts based on best-track data for right-front quadrant cases.

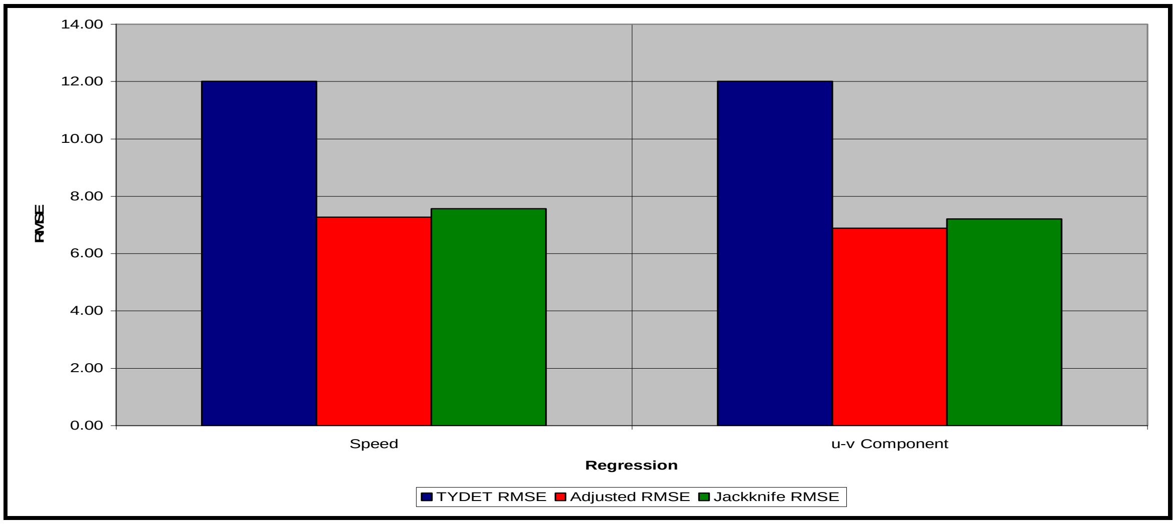


Figure 58. As in Figure 57, except for storms in which Kadena AB is in the right-rear quadrant.

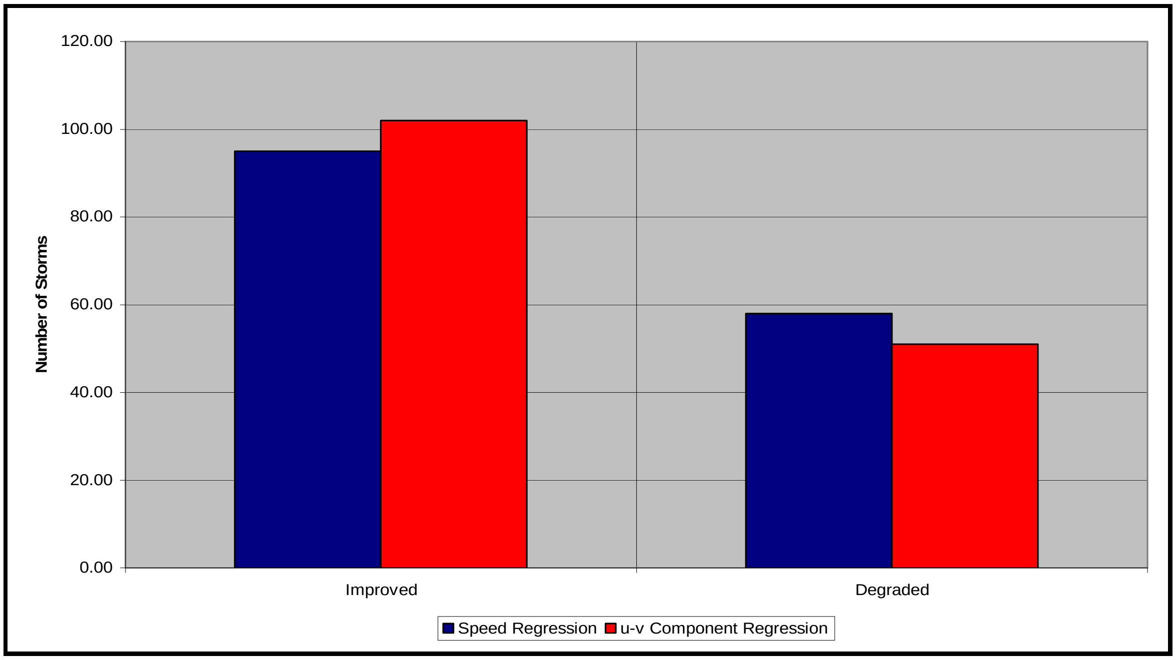


Figure 59. Number of cross-wind forecasts improved (left) or degraded (right) for the cases where the values from the speed regression (blue) and adjusted speed and direction from u- and v-components (red) when the regressions were based on best-track data. The values were calculated for combined right-front and right-rear quadrant storms affecting Kadena AB.

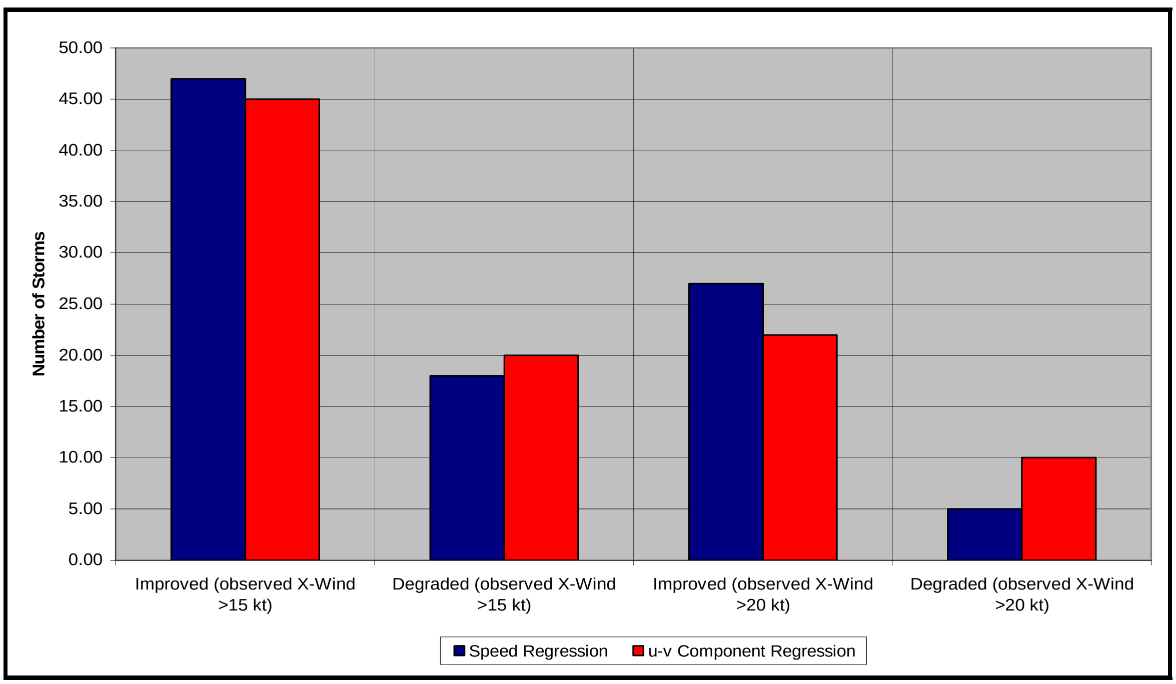


Figure 60. Similar to Figure 62, except for cases in which the cross-wind component was greater than 15 kt (left two groups) and 20 kt (right two groups).

The errors in TYDET forecasts based on best-track data were addressed through a series of linear regressions with predictors such as TC size, symmetry, and range/bearing into the TYDET program. The regressions provided adjusted forecast values that were then compared with the original TYDET forecast to calculate the improvement. Overall, an improvement in the TYDET forecasts was achieved when the best-track data were used as inputs to TYDET.

#### 4. Cross-Wind Improvements Using JTWC Forecasts

The best-track data, which represent essentially perfect inputs to TYDET, are not representative of the inputs from the JTWC forecast, which adds another source of error to the TYDET model. These additional errors are evident when the regression adjustments generated with the JTWC forecast as input were applied to the TYDET forecast values. The cross-wind RMSE was improved in both the right-front (Figure 61) and the right-rear (Figure 62) quadrant cases when the speed-only regressions were used to adjust TYDET wind speeds that were used in the cross-wind calculations. In the right-rear quadrant cases, the 0-hour forecast interval has a lower RMSE than the baseline best-track RMSE. In this case, the slight 0-hour forecast error actually improves TYDET systematic errors and therefore the RMSE is better. The adjusted forecast RMSEs are improved for all forecast intervals when Kadena AB is in the right-front or the right-rear quadrant. When Kadena AB is in the right-front quadrant the cross-wind RMSE is steady with similar improvement for all forecast intervals (Figure 61). When Kadena AB is in the right-rear quadrant, there is much more variability. At the 24- and 48-hour forecast interval the improvement of the jackknife adjusted RMSE is less than one, but at the 36-hour forecast interval the RMSE shows improvement of nearly five.

The RMSE for the cross-wind forecasts when the u- and v- component regressions are used for the adjustments are not improved as much as with the speed-only adjustments. Storms with Kadena AB in the right-front (Figure 63) and the right-rear (Figure 64) quadrant both minimally improved and both become worse than the original TYDET forecast at 48 hours. One explanation is that this poor performance may be due to a sampling issue. Whereas the speed-only regression did show improvement throughout the forecast period and the u- and v-component regressions do not show this improvement, it is possible that the wind direction is more difficult, if not impossible, to improve in the TYDET program. At least for this sample, it can be concluded that the direction adjustment based on the u- and v-component regressions does not help the TYDET cross-wind forecast and it is better to just apply the speed correction. Even when the corrected u- and v-component adjusted speed and the original TYDET forecast direction were used to calculate the cross-wind, little to no improvement was observed. Therefore, the cases with degraded direction adjustments may overly impact the cross-wind forecasts.

The numbers of improved and degraded cross-wind forecasts for both the speed regression (Figure 65) and the u- and v-component (Figure 66) regression were calculated. One extreme error or outlier can create a deceiving average RMSE that is not representative of the overall improvement made to the TYDET cross-wind forecast. The total number of improved forecasts is once again higher when the speed adjustments from the speed only regression were used than when the adjusted speeds and directions were based on the u- and v-component regressions. However, the numbers of degraded forecasts when the speed regression was used is almost as large as those that are improved which accounts for the relatively poor performance in Figure 62. In the case of the u- and v-component regressions (Figure 66), the numbers of degraded 36-hour and 48-hour forecasts actually exceeded the numbers of improved forecasts. Thus, it is not surprising that the 48-hour forecasts in Figure 64 have higher RMSE than the original TYDET forecast.

The numbers of adjusted cross-wind forecasts were improved or degraded when the observed cross-winds were in excess of certain critical levels was again calculated. Using the 15- and 20-knot cross-wind thresholds (Figures 67 and 68), there are nearly equal numbers of improvements and degradations at the various forecast intervals even for the cross-wind adjustments using the speed regressions as well as the u- and v-component regressions. The lack of a majority in the numbers of improved cases is due to the impact of wind direction errors on the cross-winds.

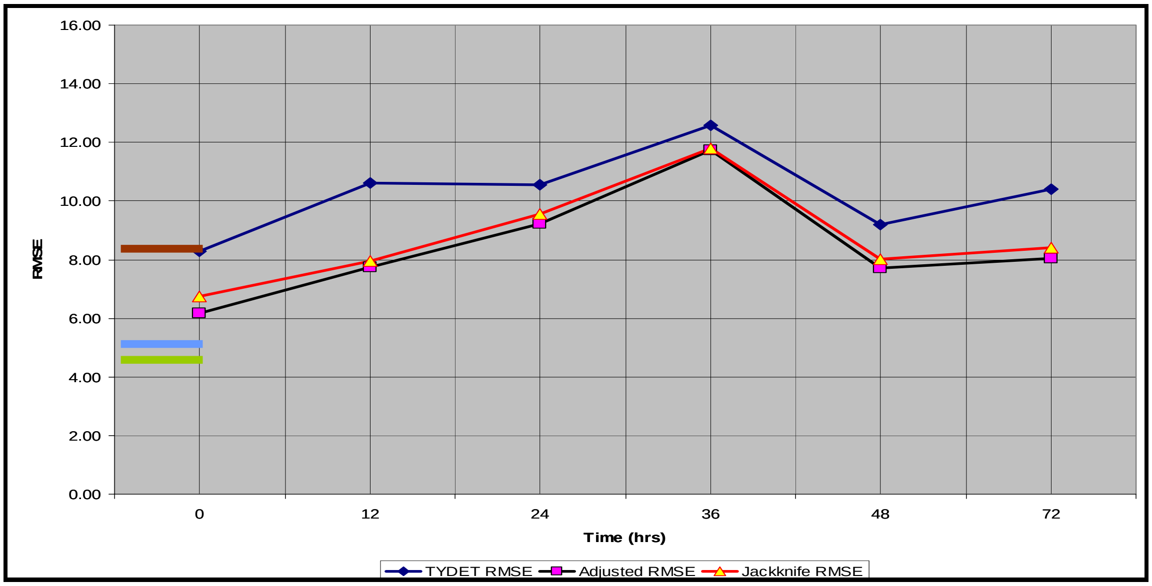


Figure 61. Cross-wind RMSE (kt) for the original TYDET winds (blue), adjusted winds (black)), and the jackknife winds (red) based on the speed regression for the storms in which Kadena AB is in the right-front quadrant. The values for the time 0 h that are derived from best-track values are shown to the left as a baseline for these results of regressions based on JTWC forecasts at the times (h) shown.

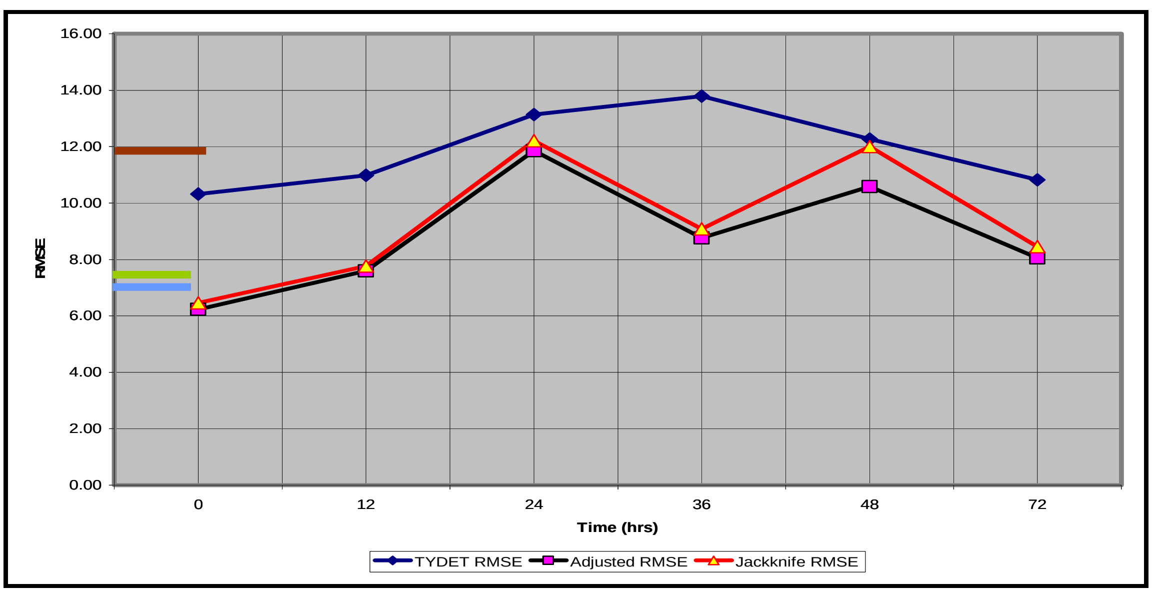


Figure 62. As in Figure 61, except for storms in which Kadena AB is in the right-rear quadrant.

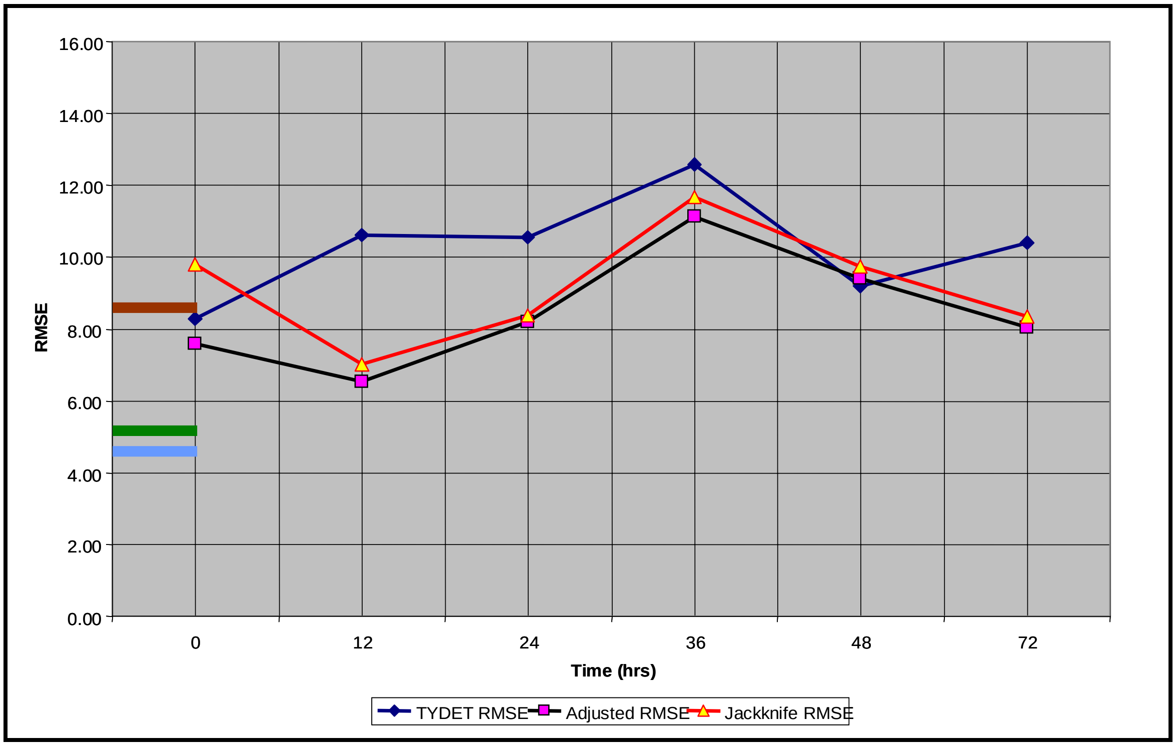


Figure 63. As in Figure 61, except the u- and v-component regression adjustments are applied to the original TYDET cross-wind forecasts.

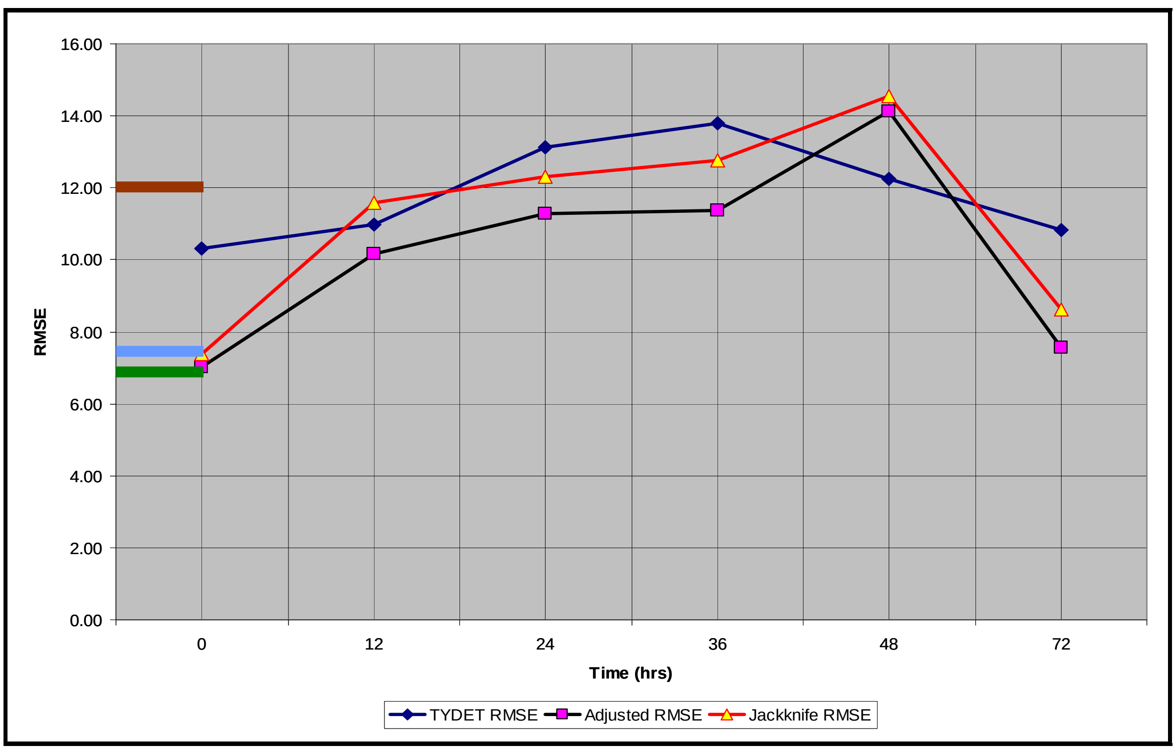


Figure 64. As in Figure 62, except the u- and v-component regression adjustments are applied to the original TYDET cross-wind forecasts.

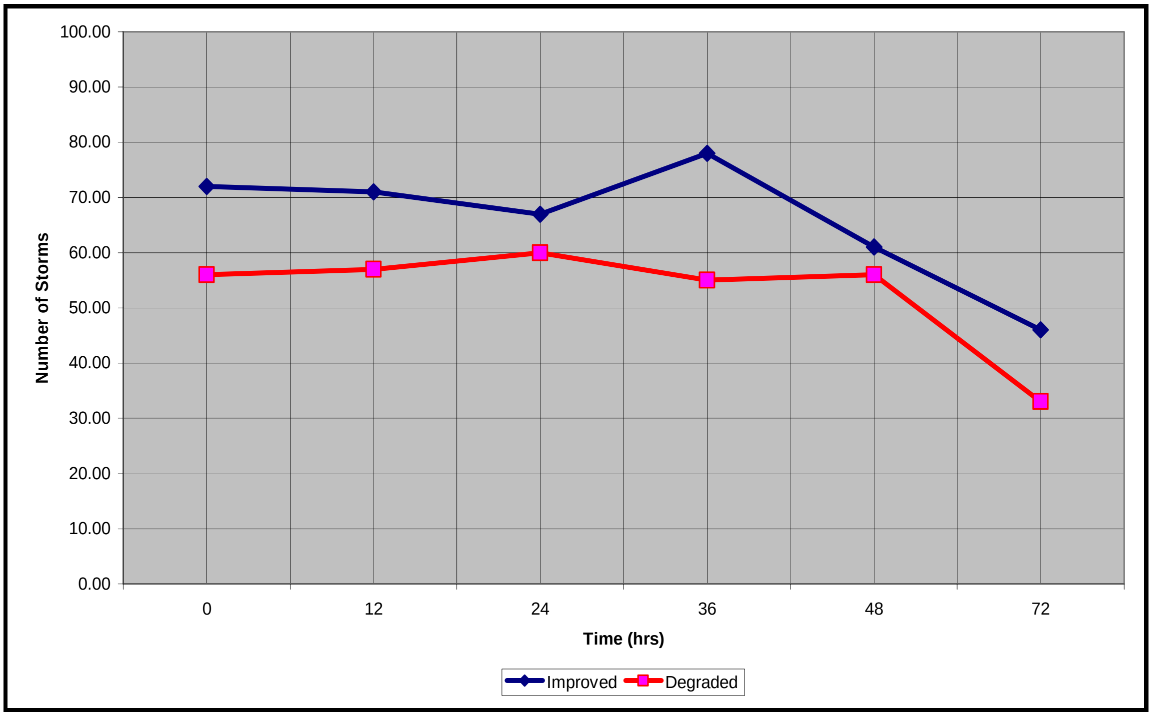


Figure 65. Numbers of cross-wind forecasts improved (blue) and degraded (red) for the cases in which the values from the speed regression were used. The values were calculated for the combined sample of storms in which Kadena AB was in the right-front and right-rear quadrant storms affecting Kadena AB using JTWC forecast data.

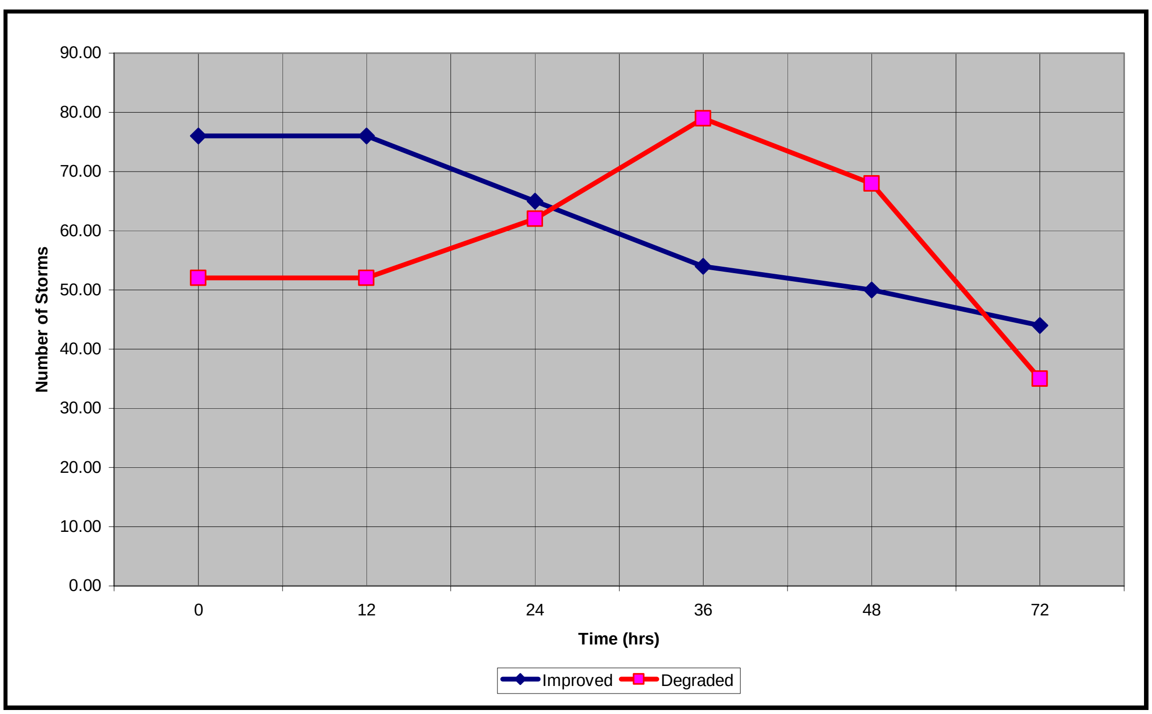


Figure 66. As in Figure 65, except using the u- and v-component regressions.

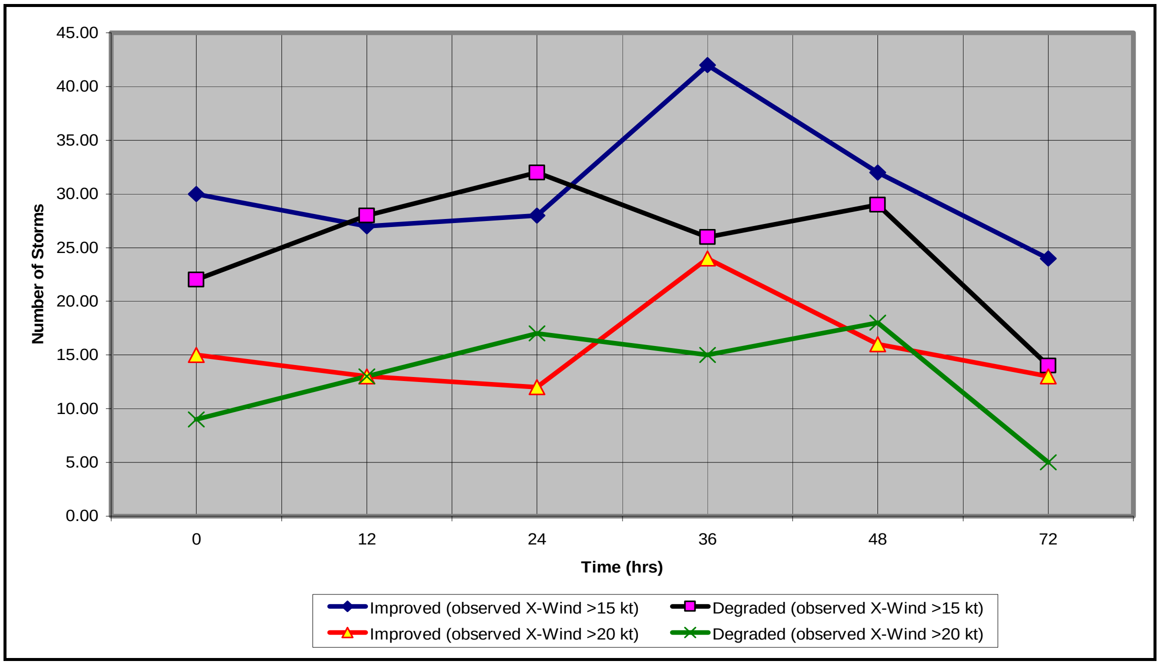


Figure 67. Numbers of cross-wind forecasts that were improved or degraded for the cases when the observed cross-winds were greater than 15 (top two curves) and 20 (bottom two curves) knots and the adjusted values from the speed regression were used. The values were calculated for the combined sample of storms in which Kadena Ab was in the right-front and right-rear quadrants using the JTWC forecasts.

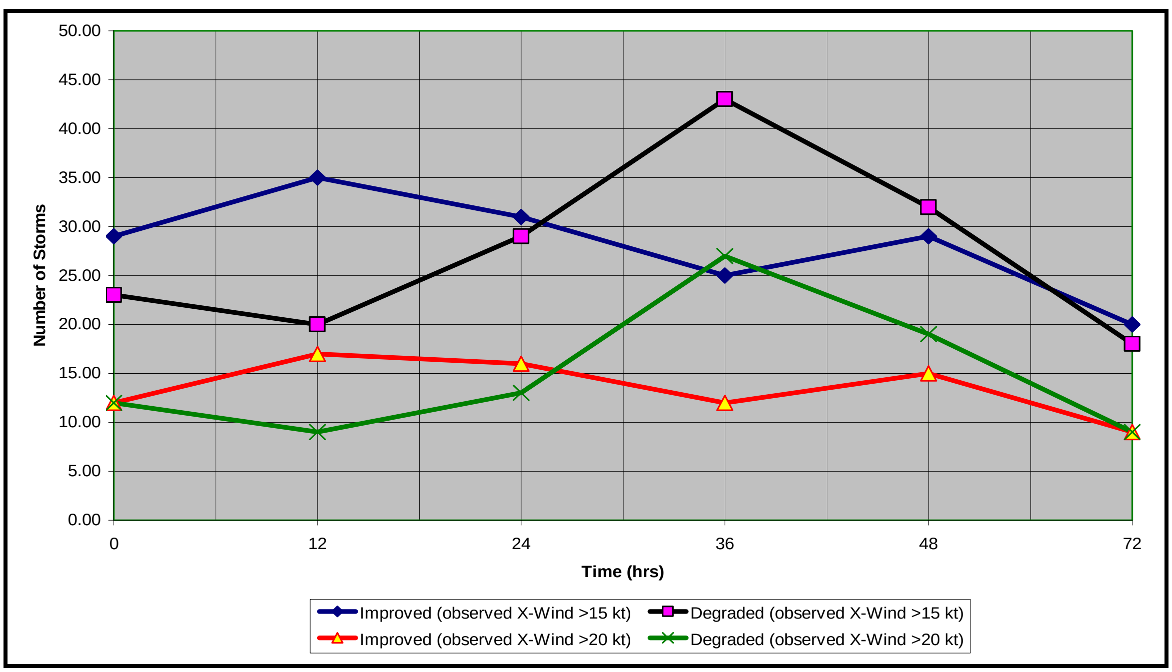


Figure 68. As in Figure 67, except using the adjustments from the for u- and v-component regressions.

## 5. Case Studies

### *a. Improved Wind Speed Forecast with Degraded Cross-wind Forecast*

A number of times the jackknife-adjusted wind speed forecast was improved, but the cross-wind forecast was degraded. These cases were examined to assess the impact of wind direction errors on the cross-wind calculation. One example of this scenario for each forecast period using the speed regression is shown in Table 2.

**0-Hour**

**Case: Speed improvement = -2.90, X-wind degraded by +6.55**

| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
|---|---|---|---|---|
| Speed | 21 | 29 | 16.25 | 15.9 |
| Direction | 100 | 80 | 80 | 80 |
| X-wind | 16.09 | 14.5 | 8.26 | 7.95 |

**12-Hour**

**Case: Speed improvement = -13.02, X-wind degraded by +4.46**

| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
|---|---|---|---|---|
| Speed | 21 | 41 | 27.62 | 27.98 |
| Direction | 110 | 70 | 70 | 70 |
| X-wind | 18.19 | 14.03 | 9.46 | 9.58 |

**24-Hour**

**Case: Speed improvement = -7.83, X-wind degraded by +7.83**

| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
|---|---|---|---|---|
| Speed | 37 | 17 | 25.72 | 24.83 |
| Direction | 210 | 140 | 140 | 140 |
| X-wind | 12.65 | 17 | 25.72 | 24.83 |

**36-Hour**

**Case: Speed improvement = -7.90, X-wind degraded by +7.90**

| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
|---|---|---|---|---|
| Speed | 37 | 18 | 26.42 | 25.9 |
| Direction | 210 | 140 | 140 | 140 |
| X-wind | 12.65 | 18 | 26.42 | 25.9 |

**48-Hour**

**Case: Speed improvement = -2.76, X-wind degraded by +9.80**

| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
|---|---|---|---|---|
| Speed | 13 | 4 | 18.84 | 19.24 |
| Direction | 60 | 90 | 90 | 90 |
| X-wind | 2.26 | 2.57 | 12.11 | 12.37 |

**72-Hour**

**Case: Speed improvement = -5.36, X-wind degraded by +6.64**

| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
|---|---|---|---|---|
| Speed | 14 | 8 | 14.58 | 14.64 |
| Direction | 210 | 140 | 140 | 140 |
| X-wind | 4.79 | 8 | 14.58 | 14.64 |

Table 2. Examples of cases in which the wind speed forecast was improved, but the cross-wind forecast was degraded.

Taking into consideration that the runway heading at Kadena AB is 230/050, the reason the cross-wind forecast was not improved was because of a change in the wind direction that caused the cross-wind component to increase or decrease. In the 0-hour, 12-hour and the 48-hour cases, the cross-wind component is smaller. Therefore, even though the wind speed is closer to the observed wind speed for those times, the cross-wind is degraded. In the 24-hour, 36-hour, and 72-hour cases, the cross-wind component is greater than the observed wind direction. For example, the observed wind direction of 210 degrees at 72-hours is a 20 degree cross-runway direction. The adjusted forecast has a wind direction of 140, which is a 90 degree cross-runway direction. Therefore, even though the wind speed accuracy is improved by over five knots, the cross-wind is in error by over six knots. This is an example of when the linear regression procedure improved the speed forecast, but due to the difficulty in forecasting the direction correctly, the cross-wind forecast was not improved.

#### *b. Degraded Wind Speed Forecast with Improved Cross-Wind Forecast*

Another scenario was when the adjusted wind speed forecast was worse than the original TYDET forecast, and yet the cross-wind forecast was improved (Table 3). For each of the time intervals examined, the scenario was essentially the same. The wind direction forecast improvement offset the increase in the wind speed error such that the cross-wind forecast was actually improved. For example, the original TYDET 12-h wind speed forecast was 36 knots and the wind direction was 200 degrees, which produced an under-forecast by one knot wind speed and a 10 degree wind direction error, and a larger cross-wind component than the observed cross-wind component by 10 degrees. The wind speed was adjusted and was decreased to 30.2 knots, which increased the error to +5.8 knots. Because the wind direction error was still 10 degrees, the decrease in wind speed actually offset some of the error due to the incorrectly forecast wind direction.

| **0-Hour** | | | | |
|---|---|---|---|---|
| **Case: Speed degraded by +21.45, X-wind improved by -16.43** | | | | |
| | **Observation** | **TYDET** | **Adjusted: Dependent Data** | **Adjust Jackknife Data** |
| **Speed** | 80 | 58 | 50.62 | 36.55 |
| **Direction** | 210 | 360 | 360 | 360 |
| **X-wind** | 27.36 | 44.44 | 38.78 | 28 |
| **12-Hour** | | | | |
| **Case: Speed degraded by +5.80, X-wind improved by -2.90** | | | | |
| | **Observation** | **TYDET** | **Adjusted: Dependent Data** | **Adjust Jackknife Data** |
| **Speed** | 37 | 36 | 30.55 | 30.2 |
| **Direction** | 210 | 200 | 200 | 200 |
| **X-wind** | 12.65 | 18 | 15.28 | 15.1 |
| **24-Hour** | | | | |
| **Case: Speed degraded by +6.93, X-wind improved by -5.31** | | | | |
| | **Observation** | **TYDET** | **Adjusted: Dependent Data** | **Adjust Jackknife Data** |
| **Speed** | 31 | 31 | 24.38 | 24.07 |
| **Direction** | 70 | 100 | 100 | 100 |
| **X-wind** | 10.61 | 23.75 | 18.67 | 18.44 |
| **36-Hour** | | | | |
| **Case: Speed degraded by +2.16, X-wind improved by -15.92** | | | | |
| | **Observation** | **TYDET** | **Adjusted: Dependent Data** | **Adjust Jackknife Data** |
| **Speed** | 47 | 54 | 42.48 | 37.84 |
| **Direction** | 220 | 130 | 130 | 130 |
| **X-wind** | 8.16 | 53.18 | 41.84 | 37.26 |
| **48-Hour** | | | | |
| **Case: Speed degraded by +5.46, X-wind improved by -4.73** | | | | |
| | **Observation** | **TYDET** | **Adjusted: Dependent Data** | **Adjust Jackknife Data** |
| **Speed** | 22 | 20 | 17.61 | 17.32 |
| **Direction** | 200 | 170 | 170 | 170 |
| **X-wind** | 11 | 17.32 | 15.25 | 15.59 |
| **72-Hour** | | | | |
| **Case: Speed degraded by +6.53, X-wind improved by -5.61** | | | | |
| | **Observation** | **TYDET** | **Adjusted: Dependent Data** | **Adjust Jackknife Data** |
| **Speed** | 33 | 31 | 24.82 | 24.47 |
| **Direction** | 90 | 110 | 110 | 110 |
| **X-wind** | 21.22 | 26.85 | 21.5 | 21.2 |

Table 3. Example in which the wind speed forecast was degraded, but the cross-wind forecast was improved.

Another example is the 36-hour case in Table 3 in which the original TYDET wind speed forecast is an over-forecast by 8 knots, but the adjusted wind speed is an under-forecast by over nine knots. The wind direction forecast of 130 degrees produced a cross-wind component of 80 degrees instead of the cross-wind component of 10 degrees based on the observed wind direction of 220 degrees. Therefore, when the wind speed forecast decreases and the wind direction forecast stays the same, the cross-wind decreases.

Although the examples in Table 3 are just from the speed-only regression, the results when both the wind speed and the direction were adjusted by using the u- and v-component regressions were similar. The only difference is that the direction forecast changes in the u- and v- regressions and the original TYDET wind direction was used in the speed-only regression. Because one more variable was changed in the u- and v-regressions, more variability in the results was created. The results as far as increased or decreased wind direction errors being offset or enhanced by increased or decreased wind speed errors were the same.

### *c. Improved Wind Speed Forecast with Improved Cross-Wind Forecast*

The most desired scenario is that both wind speed forecast and the cross-wind forecast are improved, which was the goal of the study. Table 4 illustrates an example for each forecast interval for the speed-regression cases.

In all of the examples, the original TYDET wind speed forecast was too high, but the cross-wind component direction was accurate. Even if the wind direction was not correct, the cross-wind component forecast was accurate. The 12-hour forecast illustrates this scenario. The observed wind direction of 120 degrees produces a cross-wind direction of 70 degrees. The original TYDET forecast wind direction is 290 degrees for a cross-wind direction of 60 degrees. Even though the wind direction forecast is almost 180 degrees incorrect, the cross-wind direction is very similar, which allows the cross-wind to be improved by over 20 knots.

Most of the cases in which the wind speed forecast improves and the cross-wind forecast is better involve times when the wind direction is accurately forecast. An example of this is the 48-hour case. The wind direction is forecast to be 140 degrees and the observation is 120 degrees, which leads to only a small difference in the cross-wind direction. Because the wind direction is accurate, the wind speed forecast improvement of greater than 15 knots then creates a greater than 15 knot cross-wind forecast improvement.

For most of the speed-only regression cases, the improvement in speed and improvement in cross-wind scenario occurred, and some of the improvements were quite dramatic. Cross-wind forecasts were improved by 15 knots on numerous occasions (Table 4).

| 0-Hour | | | | |
|---|---|---|---|---|
| Case: Speed Improvement -11.70, X-wind improvement -11.88 | | | | |
| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
| Speed | 29 | 46 | 33.36 | 34.12 |
| Direction | 160 | 150 | 150 | 150 |
| X-wind | 27.25 | 45.3 | 32.86 | 33.6 |
| 12-Hour | | | | |
| Case: Speed Improvement -23.9, X-wind improvement -20.71 | | | | |
| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
| Speed | 24 | 51 | 26.68 | 27.1 |
| Direction | 120 | 290 | 290 | 290 |
| X-wind | 22.55 | 44.19 | 23.12 | 23.48 |
| 24-Hour | | | | |
| Case: Speed Improvement -14.02, X-wind improvement -14.02 | | | | |
| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
| Speed | 17 | 42 | 26.47 | 27.98 |
| Direction | 160 | 140 | 140 | 140 |
| X-wind | 15.97 | 42 | 26.47 | 27.98 |
| 36-Hour | | | | |
| Case: Speed Improvement -10.85, X-wind improvement -19.40 | | | | |
| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
| Speed | 30 | 53 | 40.1 | 42.15 |
| Direction | 140 | 170 | 170 | 170 |
| X-wind | 30 | 45.9 | 34.72 | 36.5 |
| 48-Hour | | | | |
| Case: Speed Improvement -15.52, X-wind improvement -15.52 | | | | |
| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
| Speed | 31 | 53 | 32.79 | 37.48 |
| Direction | 120 | 140 | 140 | 140 |
| X-wind | 29.13 | 53 | 32.79 | 37.48 |
| 72-Hour | | | | |
| Case: Speed Improvement -18.62, X-wind improvement -18.34 | | | | |
| | Observation | TYDET | Adjusted: Dependent Data | Adjust Jackknife Data |
| Speed | 20 | 48 | 27.47 | 29.38 |
| Direction | 90 | 310 | 310 | 310 |
| X-wind | 12.86 | 47.27 | 27.05 | 28.93 |

Table 4. Example in which the wind speed forecast was improved, and the cross-wind forecast was also improved.

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# IV. SUMMARY AND CONCLUSIONS

## A. SUMMARY

The objective of this study was to examine the application of the TYDET model at Kadena AB, Japan to determine systematic errors and to add corrections to the forecast to account for these errors. Twenty-two storms dating from 2001-2005 were analyzed for systematic errors. The errors were identified as being due to differences in the TYDET model as well as to input parameters. By utilizing the best-track data, as inputs to TYDET, which is equivalent to defining perfect inputs, errors were determined that were due solely to the inherent inadequacies of the TYDET model. Lack of storm size and asymmetry considerations in the TYDET model was a source of error that needed to be corrected if the forecasts were to be improved.

The TYDET model has a bias to over-forecast wind speeds when the storm was to the west of Kadena AB and to under-forecast conditions when the storm was to the south. These errors were partly due to size, since the small storms to the west led to larger over-forecasts of the Kadena AB winds than caused by the large storms to the west. Although the wind speeds at Kadena AB for large storms, were not under-forecast as one might expect, a decrease in the over-forecast errors by the original TYDET did occur when storm size was taken into account. That is, the bias in the original TYDET to over-forecast Kadena AB winds when the storm is to the west is decreased if the size of the storm is also considered.

Some of the differences in the wind errors from when all storms were combined and when the storms were divided into the two size categories could not be explained by size alone. The asymmetry was determined to cause subtle changes in the TYDET errors within the two size categories. Some storms were so asymmetric that one of the quadrants within a small storm may have the same effect as the large storm characteristics. At least in certain quadrants, the asymmetric small storm may influence the Kadena AB winds as much as a large storm would.  A similar effect also occurred with large storms that were highly asymmetric in that they would influence Kadena AB winds much as a small storm would.

Once the errors due solely to TYDET were examined using the best-track data, the JTWC forecasts for the 0-, 12-, 24-, 36-, 48- and 72-hour were input in TYDET to examine the errors due to the JTWC forecast errors.  The track errors may change which storm quadrant is affecting the Kadena AB winds.  The average JTWC track errors for all storms increased from eight nautical miles for the 0-hour forecast to 155 n mi for the 72-hour forecast.

The average size forecast error by JTWC ranged from an under-estimate of five nautical miles for the 0-hour forecast to almost 60 n mi for 72hours.  These errors again may cause the storm to be classified in the incorrect size category, and therefore make it difficult to accurately add the size-based correction to TYDET.

The inaccuracies in the JTWC forecasts of the 34-knot wind radii also led to problems when trying to classify storms into asymmetry categories such that some storms were forecast to be in the opposite asymmetry category.  The average asymmetry errors ranged from an under-forecast of 1-2 n mi at the 0-hour forecast to an under-forecast of 15 n mi for the 36-hour forecast.  Such a 36-hour error can be huge when considering the threshold for the difference between a symmetric and an asymmetric storm is 30 n mi.  The asymmetry errors decreased after 36-hours.  Therefore, it is necessary to correct for the asymmetry biases in the JTWC forecast if the TYDET forecast is to be corrected adequately.

The JTWC wind speed errors when all of the storms were considered were near zero until the 24-hour forecast and after that time the values were underestimated.  These under-forecast winds ranged from one to two knots at the 24-hour forecast to four knots at the 72-hour forecast.  These JTWC errors resulted in similarly under-forecast cross-wind forecasts of two knots at 24 hours and nearly five knots at  72 hours.

An inverse linear relationship between TYDET wind speed errors at Okinawa versus range, storm size, and asymmetry errors was identified. When the storms were forecast to be farther from Okinawa than observed, and the storm size was under-forecast, the wind speeds were under-forecast as well. The opposite was true when the storm distance from Kadena AB was under-forecast and the size was over-forecast. The statistical relationships among all of these variables indicated the need for size and asymmetry adjustments to be included in the TYDET program.

Having identified the systematic errors in the TYDET forecast when both the “perfect” best-track data and the JTWC forecasts were input in the TYDET model, the adjustments to the original TYDET forecast were determined through a series of linear regressions that included size and asymmetry predictiors when they were statistically relevant. The regressions that included TYDET speed, storm size and asymmetry provided the most improvement.

The wind speed adjustments, when both the best-track data and the JTWC forecasts were input, led to improvements over the output TYDET forecast. The wind speed RMSE decreased by nearly one-third when the speed regression used the best-track values to adjust the TYDET forecast. The RMSE for all of the forecast time intervals and the best-track forecasts were lowered for all of the wind speed regressions tested.

The cross-wind RMSE were also smaller for all time intervals for both the speed and the u- and v-component regressions. Unfortunately, the number of cross-wind forecasts generated from the values obtained from the u- and v-component regressions had a few time intervals at which more forecasts were degraded rather than improved. This was seemingly due more to the difficulty to adjust the wind direction or the cross-wind component with respect to the runway at Kadena AB, rather than an inability to generate useful adjustments to the speed forecast.

The factors as to why the speed RMSE was improved by the regressions for all time periods, but not the cross-wind RMSE, was examined for individual cases in which the speed error decreased, but the cross-wind error increased. The fact that some wind speeds improved and the cross-winds did not again highlighted the difficulty of constantly improving on the wind direction adjustment using these regressions. Some seemingly contradictory scenarios arise in which the speed forecast is degraded when the cross-wind forecast is improved, or the speed forecast is improved when the cross-wind was degraded. Because of the situations in which the u- and v-component regressions made many of the cross-wind forecasts worse, the adjusted speed generated by using the speed-only regression is the suggested method to use in calculating the cross-wind component at Kadena AB.

The goal of this study was to evaluate the wind forecasts at Kadena AB generated by TYDET and to show that an improved TYDET can be accomplished by reducing the systematic errors. This evaluation was done through a two-step process. The first evaluation step was to run the TYDET model with the best-track data and than compare it with the JTWC forecasts as input. The TYDET model outputs of wind speed, direction, and cross-winds were then adjusted using the regressions to predict errors. Based on these outputs from the linear regression technique, the original TYDET forecast may then be adjusted.

## B. FUTURE RESEARCH

Several additional research topics should be examined. The first is to continue the study of TYDET at Kadena AB and to evaluate the errors after these regressions have been applied to correct errors when the left-front and left-rear quadrants of storms are forecast to affect Kadena AB. Additional storms should be added to the data base that will include the wind radii of the storms so that the statistical certainty of the results can be improved.

Another area of research would be to use the methods developed here to create a similar product for the other Pacific bases. While not perfect, the TYDET model does give useful guidance. This study of its biases and errors indicates it is possible to produce an accurate and helpful source of forecast guidance. Replicating this program for other bases would require compiling the best-track data for storms affecting those bases and creating a database similar to the one that exists for Kadena AB. Once the database is created, the same methods that have been applied here could be used to evaluate the accuracy of the model with just the climatological data and then with the regression adjustments for size and asymmetry.

Other research could focus on the inner grid of the TYDET program. Many of the large errors occurred close to Kadena AB within the inner grid. Although the improvements made to TYDET helped to improve the inner grid forecasts as well, more study to address the variability of wind speed and direction caused by a storm passing near or directly over Kadena AB would be of great importance to improving TYDET as well.

Another possible improvement to minimize the limitations and increase the accuracy of the TYDET forecast guidance would be to include remote sensing. TYDET was developed and last updated before the advent of many remote-sensing tools that have led to increased forecast accuracy and increased ability to analyze storm structure. One of these tools is the scatterometer, which can better determine the radial extent of TC winds and thus the size of the TC. With this improved ability to determine storm size, it should be possible to enter storm size in TYDET and improve the forecast guidance. WindSat data could also be used to determine the outer extent of TC winds. These methods aid in the wind radii forecasts from JTWC and thus should aid in the forecast guidance produced by TYDET. Unfortunately, aircraft reconnaissance has not been available in the western North Pacific basin since 1987, and thus aircraft reconnaissance observations are not included in the TYDET nomograms. Therefore, there must be a reliance on remote-sensing techniques for any verification and classification of TC size.

Finally, future research could include adding the 96- and 120-hour forecasts to the TYDET program. This would be challenging since these forecasts have only been available since the 2003 typhoon season. This addition to TYDET could be beneficial if enough storms are available to create a sufficient database, and then the same types of error bias corrections could be made to the forecast. Given the larger track errors at 120-h, it would obviously lead to larger TYDET wind errors, but then the entire JTWC forecast could be utilized in running TYDET for tropical cyclone-induced wind conditions at Kadena AB, Japan.

# APPENDIX

## A. TYDET FORMULAS

1) Wind Gust Speed: **Sustained Storm Wind speed*Grid Wind speed Percentage*0.01**

2) Wind speed: **Wind Gust Speed*.67**

3) Direction: **Direction from grid table**

4) Cross-wind: **Wind speed*absolute value((SIN((RADIANS(230)-RADIANS(Direction))/RADIANS(57.3))))**

5) Gust Cross-wind: **Wind Gust Speed*absolute value((SIN((RADIANS(230)-RADIANS(Direction))/RADIANS(57.3))))**

6) Extreme Gust Speed: **Sustained Storm Wind speed*Grid Gust Wind speed Percentage*0.01**

7) Distance: **(((Longitude of Storm-127.8) * 60 * COS(PI()/180 * ((Latitude of Storm+26.4)/2)))^2 + (Latitude of Storm-26.4)*60)^2)^0.5)**

## B. TYDET CLIMATOLOGY TABLES

| GR_One | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 22 | 23 | 25 | 27 | 27 | 28 | 28 | 28 | 27 | 26 | 24 |
| 2 | 23 | 25 | 27 | 29 | 31 | 32 | 32 | 32 | 31 | 28 | 26 |
| 3 | 25 | 27 | 30 | 36 | 39 | 40 | 39 | 37 | 34 | 31 | 28 |
| 4 | 25 | 29 | 36 | 43 | 50 | 49 | 43 | 40 | 36 | 32 | 29 |
| 5 | 26 | 31 | 39 | 52 | 66 | 61 | 50 | 43 | 37 | 33 | 28 |
| 6 | 27 | 32 | 40 | 50 | 68 | 100 | 55 | 45 | 36 | 30 | 27 |
| 7 | 26 | 30 | 36 | 45 | 56 | 66 | 50 | 40 | 33 | 29 | 27 |
| 8 | 25 | 27 | 32 | 38 | 41 | 43 | 39 | 34 | 30 | 27 | 25 |
| 9 | 23 | 25 | 28 | 30 | 32 | 32 | 31 | 28 | 27 | 25 | 23 |
| 10 | 20 | 23 | 25 | 27 | 27 | 27 | 26 | 25 | 23 | 22 | 20 |
| 11 | 17 | 20 | 23 | 23 | 24 | 24 | 23 | 22 | 21 | 20 | 17 |

Figure A-1. The outer grid wind speed percentages for grid points at 60 nautical mile intervals radially out from Kadena AB. The center value of 100 designates the location of Kadena AB. The far left values are row placeholders and do not figure into the calculations.

| GR Two | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 50 | 54 | 58 | 58 | 54 | 50 | 48 | 45 | 41 |
| 2 | 52 | 60 | 65 | 70 | 62 | 56 | 50 | 48 | 43 |
| 3 | 53 | 62 | 70 | 79 | 78 | 60 | 54 | 50 | 44 |
| 4 | 50 | 61 | 68 | 81 | 95 | 67 | 56 | 50 | 44 |
| 5 | 48 | 55 | 62 | 72 | 80 | 70 | 55 | 49 | 43 |
| 6 | 46 | 50 | 56 | 61 | 67 | 61 | 50 | 45 | 40 |
| 7 | 41 | 45 | 50 | 53 | 53 | 50 | 45 | 40 | 37 |

Figure A-2. The inner grid wind speed percentages for grid points at 60 nautical mile intervals radially out from Kadena AB. The center value of 95 designates the location of Kadena AB. The far left values are row placeholders and do not figure into the calculations.

| GRE One | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 26 | 35 | 42 | 48 | 51 | 52 | 52 | 51 | 49 | 47 | 45 |
| 2 | 30 | 40 | 50 | 53 | 56 | 57 | 57 | 54 | 52 | 49 | 47 |
| 3 | 36 | 47 | 53 | 58 | 61 | 63 | 61 | 58 | 55 | 52 | 49 |
| 4 | 40 | 50 | 58 | 65 | 71 | 73 | 71 | 64 | 57 | 54 | 51 |
| 5 | 43 | 53 | 62 | 72 | 82 | 87 | 80 | 70 | 59 | 56 | 53 |
| 6 | 45 | 54 | 64 | 75 | 89 | 100 | 85 | 74 | 60 | 56 | 53 |
| 7 | 43 | 53 | 62 | 73 | 81 | 87 | 83 | 70 | 59 | 56 | 53 |
| 8 | 41 | 50 | 57 | 65 | 73 | 75 | 71 | 61 | 57 | 54 | 52 |
| 9 | 36 | 43 | 50 | 55 | 58 | 59 | 58 | 55 | 53 | 51 | 48 |
| 10 | 30 | 36 | 42 | 46 | 50 | 51 | 51 | 50 | 48 | 45 | 42 |
| 11 | 27 | 30 | 35 | 38 | 41 | 43 | 43 | 43 | 41 | 38 | 36 |

Figure A-3. The outer grid gust wind speed percentages for grid points at 60 nautical mile intervals radially out from Kadena AB. The center value of 100 designates the location of Kadena AB. The far left values are row placeholders and do not figure into the calculations.

| GRE Two | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 70 | 73 | 77 | 79 | 78 | 77 | 75 | 72 | 68 |
| 2 | 72 | 78 | 82 | 90 | 88 | 82 | 79 | 75 | 70 |
| 3 | 75 | 81 | 88 | 96 | 95 | 88 | 83 | 79 | 72 |
| 4 | 76 | 81 | 89 | 99 | 100 | 90 | 85 | 81 | 73 |
| 5 | 75 | 80 | 85 | 90 | 96 | 91 | 86 | 81 | 73 |
| 6 | 73 | 78 | 81 | 85 | 88 | 88 | 83 | 80 | 70 |
| 7 | 70 | 74 | 77 | 80 | 82 | 82 | 79 | 72 | 66 |

Figure A-4. The inner grid gust wind speed percentages for grid points at 60 nautical mile intervals radially out from Kadena AB. The center value of 100 designates the location of Kadena AB. The far left values are row placeholders and do not figure into the calculations.

| DIR One | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 150 | 160 | 180 | 200 | 230 | 240 | 260 | 270 | 280 | 290 | 300 |
| 2 | 150 | 160 | 180 | 190 | 230 | 250 | 270 | 280 | 290 | 300 | 310 |
| 3 | 150 | 160 | 170 | 180 | 220 | 240 | 260 | 290 | 310 | 320 | 320 |
| 4 | 140 | 160 | 170 | 180 | 200 | 230 | 280 | 310 | 330 | 330 | 330 |
| 5 | 140 | 150 | 160 | 170 | 200 | 240 | 300 | 330 | 340 | 350 | 350 |
| 6 | 140 | 140 | 140 | 150 | 160 | 0 | 340 | 360 | 10 | 10 | 10 |
| 7 | 140 | 130 | 130 | 130 | 120 | 70 | 20 | 10 | 20 | 20 | 20 |
| 8 | 140 | 130 | 120 | 110 | 90 | 70 | 40 | 20 | 20 | 30 | 30 |
| 9 | 130 | 130 | 120 | 110 | 90 | 70 | 50 | 40 | 30 | 30 | 30 |
| 10 | 130 | 120 | 110 | 100 | 90 | 80 | 70 | 50 | 40 | 40 | 40 |
| 11 | 120 | 120 | 110 | 100 | 90 | 80 | 70 | 60 | 40 | 40 | 50 |

Figure A-5. The outer grid wind direction for grid points at 60 nautical mile intervals radially out from Kadena AB. The center value of 0 designates the location of Kadena AB. The far left values are row placeholders and do not figure into the calculations.

| DIR Two | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 180 | 190 | 200 | 210 | 230 | 260 | 300 | 310 | 320 |
| 2 | 160 | 190 | 200 | 220 | 240 | 280 | 300 | 320 | 330 |
| 3 | 160 | 170 | 200 | 210 | 250 | 300 | 320 | 330 | 340 |
| 4 | 150 | 140 | 140 | 140 | 0 | 320 | 340 | 350 | 360 |
| 5 | 140 | 140 | 140 | 130 | 100 | 30 | 10 | 360 | 360 |
| 6 | 130 | 130 | 120 | 100 | 70 | 50 | 20 | 10 | 10 |
| 7 | 120 | 120 | 110 | 90 | 70 | 50 | 30 | 20 | 10 |

Figure A-6. The inner grid wind direction for grid points at 60 nautical mile intervals radially out from Kadena AB. The center value of 0 designates the location of Kadena AB. The far left values are row placeholders and do not figure into the calculations.

## C. ADJUSTED FORECAST AND BEST-TRACK RESULTS

| Time | Quadrant | Regressed | TYDET RMSE | Adjusted RMSE | Jackknife RMSE |
|---|---|---|---|---|---|
| Best-Track | RF | Speed | 9.4355 | 4.6764 | 5.1922 |
| 0 | RF | Speed | 8.9278 | 7.0190 | 8.7898 |
| 12 | RF | Speed | 10.1007 | 5.8944 | 6.2870 |
| 24 | RF | Speed | 9.1014 | 7.1280 | 7.7504 |
| 36 | RF | Speed | 9.3776 | 7.5257 | 8.1877 |
| 48 | RF | Speed | 10.3096 | 7.1929 | 7.9461 |
| 72 | RF | Speed | 11.6629 | 8.5508 | 9.7137 |
| Best-Track | RR | Speed | 12.6739 | 6.6415 | 7.1558 |
| 0 | RR | Speed | 10.5475 | 6.2326 | 6.7481 |
| 12 | RR | Speed | 12.7863 | 9.2677 | 10.3451 |
| 24 | RR | Speed | 16.4441 | 12.4165 | 13.8725 |
| 36 | RR | Speed | 13.9909 | 6.8783 | 7.4486 |
| 48 | RR | Speed | 11.7917 | 8.8632 | 10.7770 |
| 72 | RR | Speed | 14.9546 | 6.3236 | 7.2899 |
| Best-Track | RF | u-component | 7.7034 | 4.2087 | 4.7585 |
| 0 | RF | u-component | 8.6184 | 5.1427 | 6.2717 |
| 12 | RF | u-component | 9.5153 | 6.1092 | 6.5977 |
| 24 | RF | u-component | 14.5445 | 10.1772 | 11.2647 |
| 36 | RF | u-component | 19.2885 | 14.8285 | 16.0894 |
| 48 | RF | u-component | 17.2962 | 15.9786 | 17.3451 |
| 72 | RF | u-component | 17.8527 | 15.7695 | 16.2899 |
| Best-Track | RR | u-component | 7.9943 | 7.1117 | 7.4814 |
| 0 | RR | u-component | 8.7606 | 7.5702 | 8.1805 |
| 12 | RR | u-component | 15.8183 | 15.4629 | 17.5684 |
| 24 | RR | u-component | 13.5984 | 13.0677 | 13.5855 |
| 36 | RR | u-component | 12.5300 | 10.2388 | 12.4148 |
| 48 | RR | u-component | 17.0634 | 13.8302 | 15.4204 |
| 72 | RR | u-component | 16.0565 | 13.7774 | 15.2301 |
| Best-Track | RF | v-component | 8.5587 | 6.6601 | 8.7275 |
| 0 | RF | v-component | 17.5066 | 17.0926 | 21.9250 |
| 12 | RF | v-component | 10.1319 | 8.3293 | 8.9247 |
| 24 | RF | v-component | 12.5032 | 10.4046 | 11.5764 |
| 36 | RF | v-component | 11.7238 | 11.3048 | 11.9555 |
| 48 | RF | v-component | 13.5100 | 12.5564 | 13.6828 |
| 72 | RF | v-component | 19.9647 | 18.8800 | 20.5746 |
| Best-Track | RR | v-component | 9.0625 | 6.9115 | 7.8437 |
| 0 | RR | v-component | 8.9654 | 6.6553 | 7.0747 |
| 12 | RR | v-component | 18.4757 | 17.2154 | 19.9113 |
| 24 | RR | v-component | 20.1266 | 17.6513 | 20.0757 |
| 36 | RR | v-component | 17.3749 | 15.6178 | 17.4127 |
| 48 | RR | v-component | 15.5192 | 14.4082 | 16.6315 |
| 72 | RR | v-component | 15.4210 | 7.5182 | 9.2908 |

Table A-1. The RMSE values when the JTWC forecast and best-track data at various intervals (column 1) are used in the TYDET model for storms with Kadena AB in either the Right-Front (RF) or Right-Rear (RR) quadrants (column 2) and for the wind variables in the Regressed (column 3) The TYDET RMSE is the RMSE before the regression, the adjusted RMSE is for the dependent data and the jackknife RMSE is from the jackknife procedure.

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