

Estimation of Tropical Cyclone Intensity Using Aqua/AMSR-E Data

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Abstract

In this study, the technique of Hoshino and Nakazawa (2007) was adopted to estimate tropical cyclone (TC) intensity using microwave imagery from the AMSR-E (Advanced Microwave Scanning Radiometer for EOS) sensor on board NASA's Aqua satellite. The results showed a close correlation with the best track data determined by the Japan Meteorological Agency, and it was found that these data could be fully utilized as reference for intensity analysis. Higher levels of objectivity and accuracy in such analysis can be expected by using this data to complement regular intensity analysis with the Dvorak method.

1. Introduction

Surface observations on land and sea, geostationary meteorological satellite imagery and data from microwave scatterometers (such as the SeaWinds sensor on board the QuikSCAT satellite) are mainly used for TC intensity analysis. However, the amounts of TC data available are limited, and more often than not they relate to areas over the sea. Analysis results obtained using the Dvorak method (Dvorak [1975, 1984]) for TC intensity estimation with geostationary meteorological satellite imagery may therefore serve as an important basis for TC intensity analysis. In the Dvorak method, however, erroneous judgment in the developing stage may create significant inaccuracies in the results of such analysis. Accordingly, analysts must take a TC's life stage into consideration when determining its intensity. To avoid erroneous results caused by the subjective judgment of analysts, a skilled analysis technique is required. Additionally, since the Dvorak method involves statistical procedures, analysis of exceptionally rapid development/weakening can be difficult. For all these reasons, establishing a basis to ascertain TC intensity other than analysis using the Dvorak method is expected to enable intensity estimation with a higher level of objectivity. This article covers and reports on the verification of TC intensity estimation using microwave imagery from the AMSR-E sensor on board the Aqua earth observation satellite using the technique of Hoshino and Nakazawa (2007).

2. Research method

2.1 Analytical tool and approach used in the research

GMSLPM/SATAID was used as the analytical tool. SATAID (Satellite Animation and Interactive Diagnosis) is a piece of software that enables PC-based satellite image analysis with a lot of functions such as displaying animation of satellite images, measuring brightness temperature and the like, as well as superimposing various meteorological data. (Meteorological Satellite Center [1999], Kumabe [2000], Kumabe [2001]). For this research, GMSLPM (a version of the SATAID capable of displaying microwave imagery) was selected.

The method of Hoshino and Nakazawa (2007) was adopted for intensity estimation. This technique uses brightness temperature distribution in the microwave frequency band of the TMI sensor on board the TRMM earth observation satellite (referred to hereafter as “TRMM/TMI”). Hoshino and Nakazawa (2007) created a formula for computation based on data collected from 1999 through 2003, and verified it using data gathered from the western North Pacific in 2004. For this verification, Hoshino used data collected from 2002 through 2004 and the same technique, with the parameters recalculated for the AMSR-E sensor on board the Aqua satellite (referred to hereafter as “Aqua/AMSR-E”), and also conducted verification using data from 2005.

Specifically, parameters such as the concentric circle/concentric annulus around the center (the parameter calculation area is that within a radius of two degrees from the TC center), the minimum/maximum/average brightness temperature and the ratio of pixels exceeding a certain threshold level were calculated based on the predetermined TC center position, and candidate values for maximum wind speed (V_{max}) were calculated using 10 regression formulas obtained from known data. The average of these candidate values was then taken as the maximum wind speed. There are two types of estimated maximum wind speed: One is calculated with the maximum wind speed from western North Pacific best track data as a known value (BT_WP), and the other is calculated with the maximum wind speed of data from the global microwave scatterometer (the SeaWinds sensor on board QuikSCAT, hereafter referred to as “QuikSCAT/SeaWinds”) as a known value (SCAT_ALL). Table 1-1 shows the formula for obtaining candidates for the maximum wind speed (V_{max}) as well as the parameters for the regression formula, and Table 1-2 describes the parameters.

In the GMSLPM satellite image display analysis software chosen for this research, 10 candidate maximum wind speed values obtained using the above-mentioned 10 regression formulas (BT_WP and SCAT_ALL) and the average values (BT_WP_Ave and SCAT_ALL_Ave) can be obtained by clicking the TC center position estimated on the Aqua/AMSR-E image shown on the computer screen. An analysis example using GMSLPM is shown in Figure 1.

Table 1-1 Regression formula used to calculate 10 candidate values for maximum wind speed (Vmax), and combinations of coefficients and parameters for calculating BT_WP (top) and SCAT_ALL (bottom)

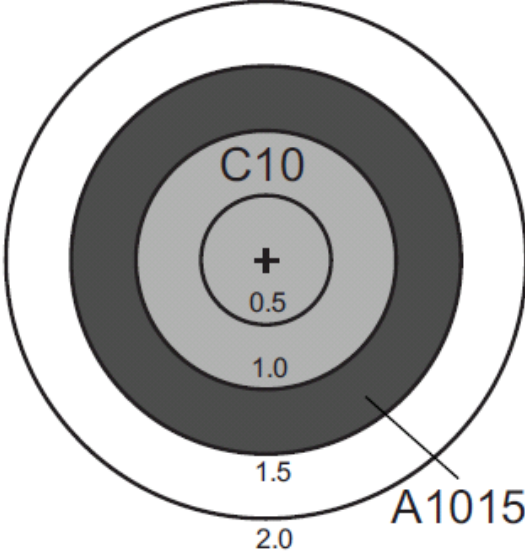
Regression formula used to obtain candidate values for maximum wind speed:

$$V_{max} = aP1 + bP2 + cP3 + d$$

| | a | P1 | b | P2 | c | P3 | d |
|----|----------|-------------------|----------|------------------|----------|------------------|----------|
| 1 | 0.099 | TB07H_AREA110_C10 | 0.31 | TB07V_MIN_C05 | 0.29 | TB10H_MIN_A0515 | -59.48 |
| 2 | 0.19 | TB07H_AREA110_C10 | 0.42 | TB10H_MIN_A0515 | 0.28 | PCT89_MEAN_A1020 | -97.47 |
| 3 | 0.57 | TB07V_MIN_C05 | 0.36 | TB10H_MIN_A0515 | 0.036 | PCT89_MIN_C10 | -115.59 |
| 4 | 0.16 | TB07H_AREA110_C10 | 0.38 | TB07V_MIN_C05 | 0.048 | PCT89_MIN_C10 | -54.04 |
| 5 | 0.13 | TB07H_AREA110_C10 | 0.30 | TB10H_MIN_A0515 | 0.22 | TB19V_MIN_C05 | -55.29 |
| 6 | 0.12 | TB07H_AREA110_C10 | 0.37 | TB07V_MIN_C05 | 0.21 | TB24H_MIN_A1015 | -90.43 |
| 7 | 0.25 | TB07H_AREA110_C10 | 0.20 | TB19H_MEAN_A1520 | 0.43 | PCT89_MEAN_A1020 | -136.12 |
| 8 | 0.12 | TB07H_AREA110_C10 | 0.37 | TB07V_MIN_C05 | 0.10 | TB19H_MEAN_A1520 | -62.86 |
| 9 | 0.52 | TB07V_MIN_C05 | 0.38 | TB10H_MIN_A0515 | 0.034 | PCT89_MIN_A1020 | -108.86 |
| 10 | 0.50 | TB07V_MIN_C05 | 0.52 | TB10H_MIN_A0515 | 0.18 | PCT89_MEAN_A1020 | -161.25 |

| | a | P1 | b | P2 | c | P3 | d |
|----|----------|----------------|----------|-------------------|----------|-----------------|----------|
| 1 | 1.30 | TB07H_MEAN_C15 | -0.19 | TB24H_AREA260_C15 | 0.32 | PCT89_MEAN_C15 | -187.65 |
| 2 | 1.10 | TB07H_MEAN_C15 | -0.15 | TB24H_MIN_A1020 | 0.34 | PCT89_MEAN_C15 | -143.00 |
| 3 | 0.93 | TB07H_MEAN_C15 | 0.17 | TB07V_MAX_C05 | 0.47 | PCT89_MEAN_C15 | -227.52 |
| 4 | 1.10 | TB07H_MEAN_C15 | -0.59 | TB07V_MIN_A1020 | 0.37 | PCT89_MEAN_C15 | -85.12 |
| 5 | 1.20 | TB07H_MEAN_C15 | -0.18 | TB19H_MIN_A0515 | 0.38 | PCT89_MEAN_C15 | -167.22 |
| 6 | 1.10 | TB07H_MEAN_C15 | -0.15 | TB19V_MEAN_A1520 | 0.37 | PCT89_MEAN_C15 | -152.32 |
| 7 | 0.99 | TB07H_MEAN_C15 | 0.053 | TB19H_MEAN_C05 | 0.45 | PCT89_MEAN_C15 | -205.12 |
| 8 | 1.10 | TB07H_MEAN_C15 | -0.24 | TB10V_MIN_A0510 | 0.34 | PCT89_MEAN_C15 | -135.98 |
| 9 | 1.00 | TB07H_MEAN_C15 | -0.15 | TB24H_MAX_A1520 | 0.38 | PCT89_MEAN_C15 | -142.07 |
| 10 | 1.20 | TB07H_MEAN_C15 | -0.24 | TB24H_AREA260_C15 | 0.035 | PCT89_MIN_A1020 | -92.49 |

Table 1-2 Description of parameters in Table 1-1

| Description of Parameters | |
|--|--|
| TB07H(V): | Brightness temperature according to horizontally (vertically) polarized waves on the 7 GHz band channel |
| TB10H(V): | Brightness temperature according to horizontally (vertically) polarized waves on the 10 GHz band channel |
| TB19H(V): | Brightness temperature according to horizontally (vertically) polarized waves on the 19 GHz band channel |
| TB24H(V): | Brightness temperature according to horizontally (vertically) polarized waves on the 24 GHz band channel |
| PCT89: | Polarization correction temperature (amount of radiation after deducting that from the sea surface) on the 89 GHz band channel ... $PCT89 = 1.818TB89V - 0.818TB89H$ |
| TB89V: | Brightness temperature of vertically polarized waves |
| TB89H: | Brightness temperature of horizontally polarized waves |
| MIN (MAX): | Minimum (maximum) brightness temperature in the area of a concentric circle and concentric annulus around the center |
| MEAN: | Mean brightness temperature in the area of a concentric circle and concentric annulus around the center |
| AREA: | Ratio of pixels exceeding a certain threshold value in the area of a concentric circle and concentric annulus around the center |
| CXX: | Area of a concentric circle around the center with a radius of X.X degrees |
| AYYZZ: | Area of a concentric annulus around the center with an inside diameter of Y.Y degrees and an outside diameter of Z.Z degrees |
| (Example 1) TB07H_AREA110_C10: Ratio of pixels for which the brightness temperature is 110 K or more in the area of a concentric circle with a radius of one degree from the center (the light gray part of the figure below) of the horizontally polarized waves on the 7 GHz band channel | |
| (Example 2) TB10V_MIN_A1015: Minimum brightness temperature in the area of a concentric annulus with a radius of 1.0 to 1.5 degrees from the center (the dark gray part of the figure below) of the vertically polarized waves on the 10 GHz band channel | |
|  <p>The diagram shows a central point marked with a '+' sign, labeled 'TC center'. Concentric circles are drawn around this center. The innermost circle is labeled 'C10' and has a radius of '0.5'. The next circle out has a radius of '1.0'. The annulus between the 1.0 and 1.5 radius circles is shaded dark gray and labeled 'A1015'. The next circle has a radius of '1.5', and the outermost circle has a radius of '2.0'.</p> | |
| + indicates the TC center | |

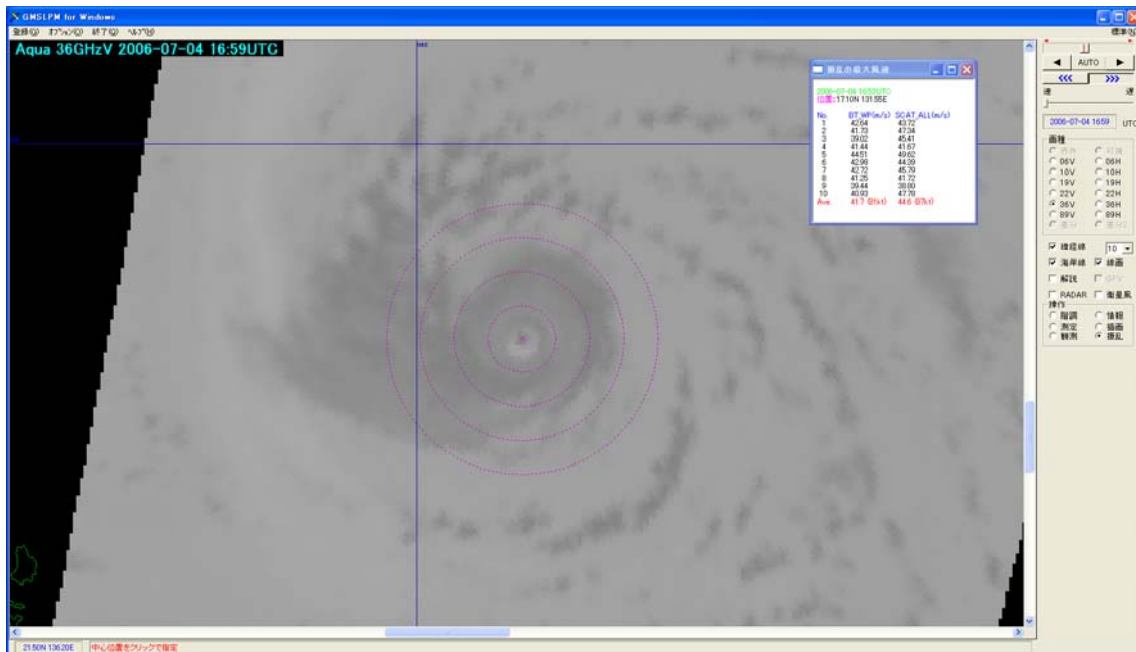


Figure 1 On-screen appearance of GMSLPM satellite image display analysis software (analysis example)

2.2 Targeted TC and methods of research

This research used TCs with TS intensity or higher analyzed as best track between June 2003 and December 2006. The data selected were those recorded while the best track TC center was in the observation range within three hours (before or after) of the Aqua/AMSR-E observation time. As the interval of the best track data covers a maximum of six hours, the time difference between Aqua/AMSR-E observation and the best track must be within three hours. Aqua/AMSR-E observation time here is rounded to the nearest hour.

For the research, images used by the Analysis Division of the Meteorological Satellite Center for TC center analytical investigation involving microwave satellite imagery and the center position obtained at that time (2003 through 2005) were chosen (Nishimura et al. [2007]). The center position was newly determined for Aqua/AMSR-E imagery from 2006. The procedures followed to determine this position were the same as those outlined by Nishimura et al. (2007) (Figure 2). Hoshino and Nakazawa (2007) determined the TC center position for hours without best track data by interpolating the best track, but in this research the center was determined using microwave imagery, which should prove to be more accurate in terms of positioning.

The TC cloud patterns of the microwave images used to estimate the center location were those given by Nishimura et al. (2007), meaning that they were different from those of the Dvorak method. Examples of these patterns are shown in Figure 3. In this report, they are described with the prefix of MW, such as MW EYE, etc. Categorization of TC cloud patterns by the Dvorak method was performed according to “Analysis and use of meteorological satellite images: Tropical cyclones” (Meteorological Satellite Center, 2004).

Knots (KT) were used as the unit of maximum wind speed as with best track data. However, Hoshino and Nakazawa (2007) used m/s in their research, so this unit was used in comparisons for accuracy verification.

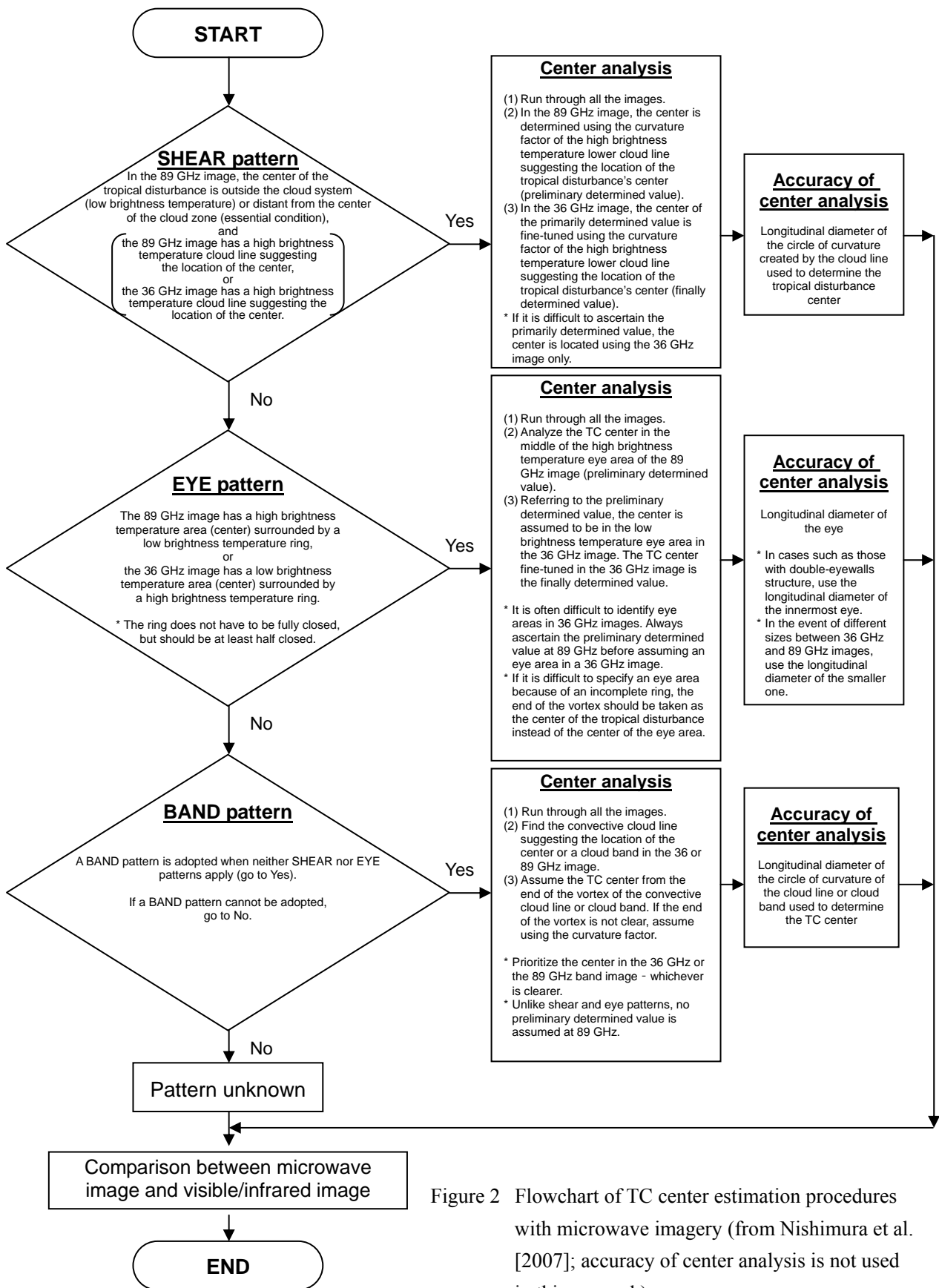
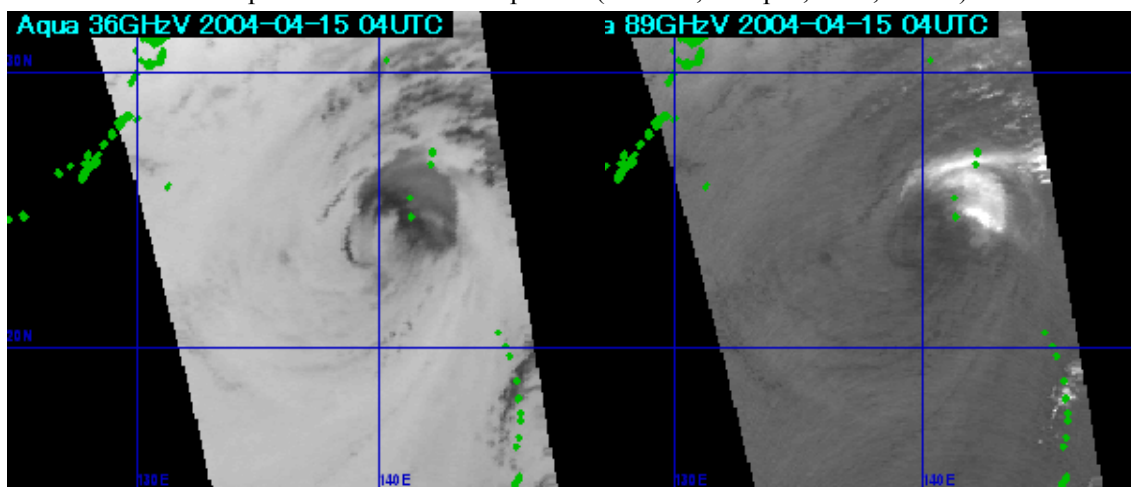
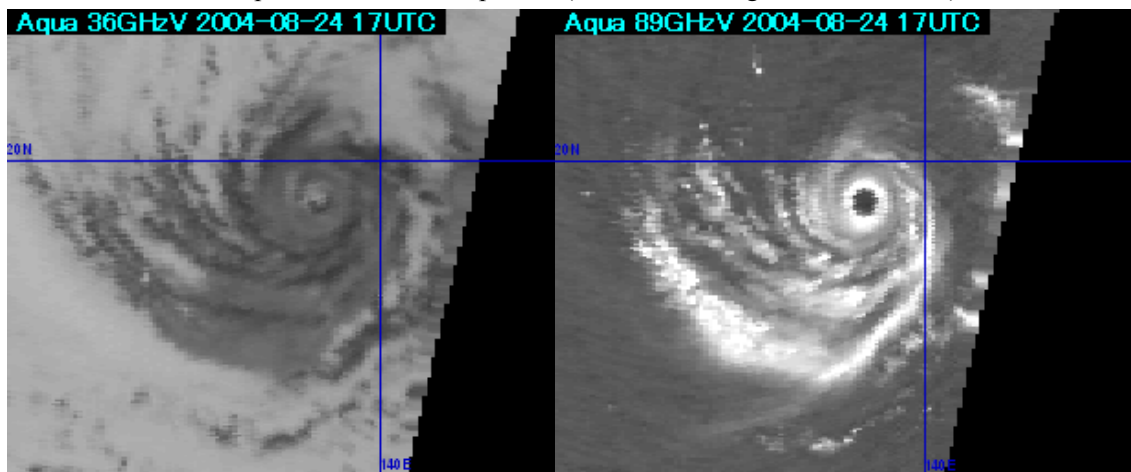


Figure 2 Flowchart of TC center estimation procedures with microwave imagery (from Nishimura et al. [2007]; accuracy of center analysis is not used in this research)

Example of an MW SHEAR pattern (04 UTC, 15 April, 2004, T0401)



Example of an MW EYE pattern (17 UTC, 24 August, 2004, T0416)



Example of an MW BAND pattern (18 UTC, 21 November, 2004, T0425)

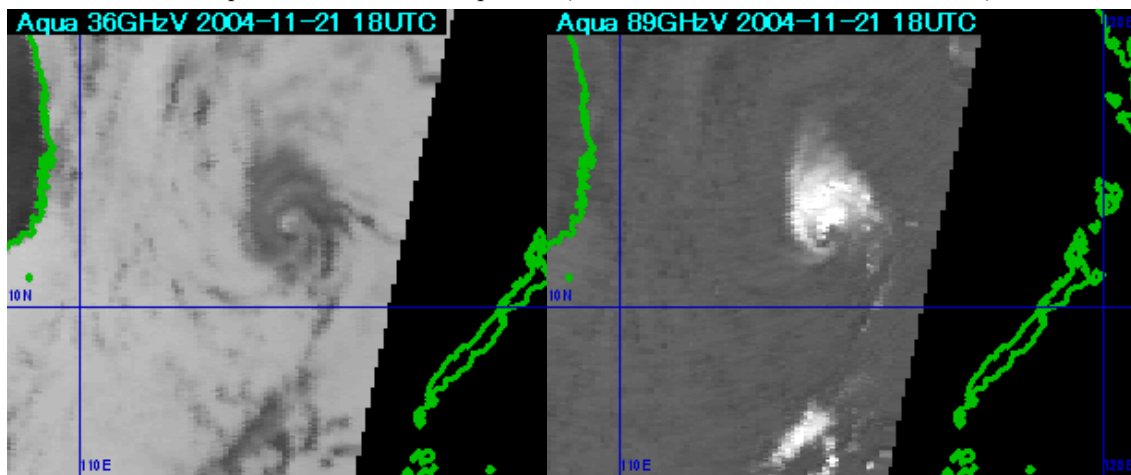


Figure 3 Examples of cloud patterns used to assume TC center locations (36 GHz on the left and 89 GHz on the right)

3. Verification results

In this study, the relationship of the best track maximum wind speed to BT_WP and SCAT_ALL was verified from various perspectives, with the maximum wind speed of the best track in the western North Pacific (as determined by the Japan Meteorological Agency) taken as a true value.

Hoshino and Nakazawa (2007) selected the maximum wind speed from QuikSCAT/SeaWinds within three degrees of latitude from the TC center and calculated SCAT_ALL. As this value is set to approach the maximum wind speed of QuikSCAT/SeaWinds, direct comparison with QuikSCAT/SeaWinds data is necessary for strict verification. However, comparison with the maximum wind speed obtained from QuikSCAT/SeaWinds data was not conducted in this study because only the best track maximum wind speed was used as a true value.

3.1 Scatter diagram of overall data: relationship of best track maximum wind speed to BT_WP and SCAT_ALL

A comparison based on the overall data for 2003 through 2005 is shown in Figure 4 (355 cases for BT_WP_Ave and 353 for SCAT_ALL_Ave). The correlation coefficients of BT_WP_Ave and SCAT_ALL_Ave to the best track maximum wind speed of these data were 0.71 and 0.22, respectively.

There is a relatively good correlation between the best track maximum wind speed and BT_WP, but SCAT_ALL_Ave values are sometimes far higher. Here, if the cases in which SCAT_ALL_Ave is 120 KT or more are excluded, the correlation coefficient becomes 0.72 (figure omitted). There are 34 cases in which SCAT_ALL_Ave is 120 KT or more, and the majority of these (30) had land within two degrees of the typhoon center position. There were also 29 cases in which SCAT_ALL_Ave was 135 KT or more, but all of them included land. This effect of land on data is discussed in the next section.

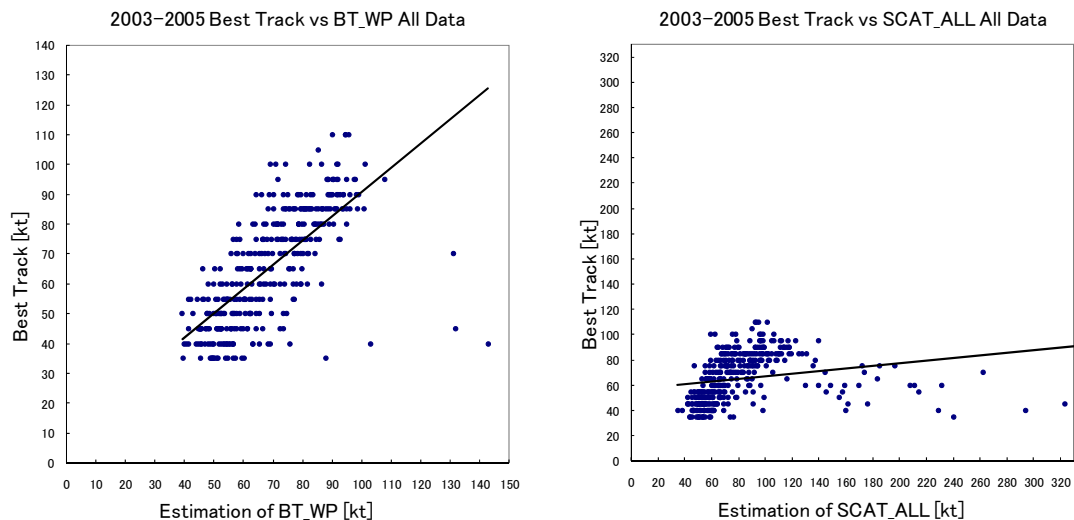


Figure 4 Scatter diagram of overall data for 2003 through 2005
Scatter diagram of best track maximum wind speed and BT_WP_Ave (left)
Scatter diagram of best track maximum wind speed and SCAT_ALL_Ave (right)
The straight line in each figure is the regression line.

3.2 Effect of land

In microwave observation, emissivity is greater on land than over the sea, and the brightness temperature is much higher on land. Figure 5 shows the results of eliminating this land effect by performing calculation after excluding an additional area of one pixel* on the outside (i.e., the sea side) of pixels judged to be land by GMSLPM satellite image display analysis software. Here, two types of data are excluded: those from which BT_WP_Ave cannot be calculated because the land coverage area is too large, and those from which the TC center position cannot be determined due to unclear TC cloud patterns in microwave images. The remaining data from 2003 through 2006 were used; the total number of cases was 470 for BT_WP_Ave and 471 for SCAT_ALL_Ave. (Data from 2006 for which the TC center position was determined in 2008 were included. It is known from the data for 2003 through 2005 that adding cases that include land within two degrees of the TC center position causes a deterioration of the correlation coefficient, so cases including land were excluded from the data for 2006. Verification was conducted using the data for 2003 through 2006 for Section 3.2 onwards.)

As a result of excluding the effect of land, the calculated BT_WP value (which shows an inherently good correlation with and minimal difference from the best track data) includes no values that are exceptionally larger than those of the best track resulting in even better correlation. The correlation coefficients of BT_WP_Ave and SCAT_ALL_Ave to the best track maximum wind speed are now 0.83 and 0.72, respectively, with the calculated SCAT_ALL_Ave value apparently showing a better correlation.

The left part of Figure 5 also shows the tendency for calculation of BT_WP_Ave on the stronger side for a weak best track maximum wind speed and BT_WP_Ave on the weaker side for a strong best track maximum wind speed. This tendency also applies to periods for a tropical depression, a TC with a maximum wind speed of less than 34 KT before development to tropical storm intensity (not included in the research cases of Section 3.3 onwards) in the best track, and BT_WP_Ave was calculated as being stronger during periods of TD status (21 cases during the whole period; table omitted).

Verification results excluding the effect of land are shown below.

* One pixel is approximately 10 km.

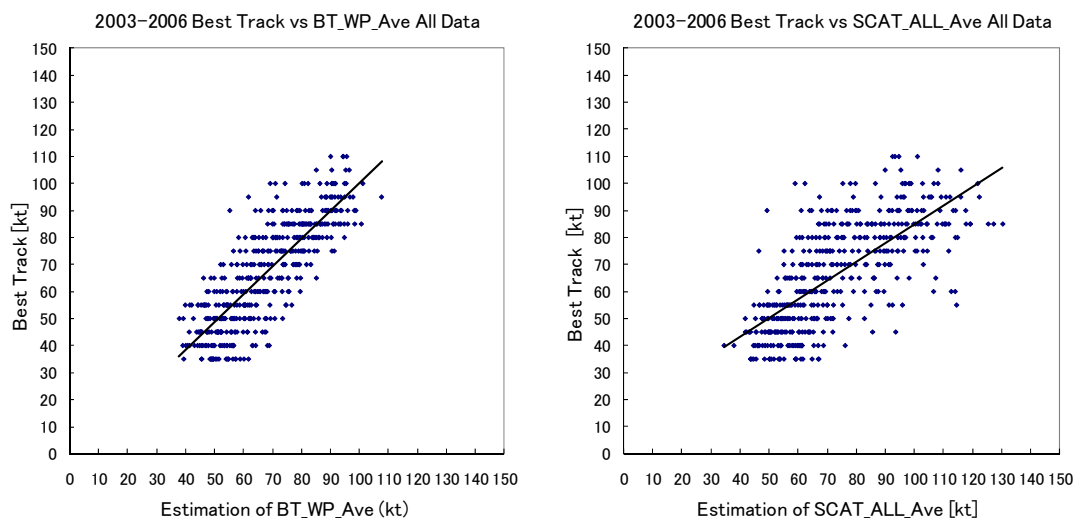


Figure 5 Scatter diagram of overall data for 2003 through 2006 excluding the effect of land
 Scatter diagram of best track maximum wind speed and BT_WP_Ave (left)
 Scatter diagram of best track maximum wind speed and SCAT_ALL_Ave (right)
 The straight line in each figure is the regression line.

3.3 Effect of partially missing imagery in the parameter calculation area or non-calculation of candidate values for maximum wind speed

As the Aqua polar orbiting satellite has a limited observation range, the TC center is not always in the center of the image, and the whole of the parameter calculation area within a two-degree radius of the TC center is not always contained in the image. The data used here have 111 cases of partially missing imagery for the parameter calculation area within a two-degree radius of the TC center. The correlation coefficient between the best track maximum wind speed and BT_WP_Ave with these missing parts is 0.83, which is the same as the corresponding coefficient derived in Section 3.2. As the effect of data with partially missing imagery in the parameter calculation area within a two-degree radius of the TC center is therefore considered insignificant, such data are used.

There are also 15 cases of data* with imagery that is partially missing for the reasons outlined above and data lacking calculation of any one of the maximum wind speed candidate values obtained from the 10 regression formulas due to the effect of land. With these missing data, the correlation coefficient between the best track maximum wind speed and BT_WP_Ave is 0.83, which is the same as the value obtained in Section 3.2 from the same data. As the effect on the calculated BT_WP_Ave value is therefore considered small even if maximum wind speed candidate values cannot be obtained, such data are used (table omitted).

* A specification of the GMSLPM software referenced in this report is that the brightness temperature statistical values of the individual frequency bands used for each regression formula must be valid for more than half the valid pixels in the calculation area. In areas where invalid pixels account for more than half of the total due to partially missing imagery or the

effect of land, the maximum wind speed cannot be obtained using a regression formula (i.e., it cannot be calculated).

3.4 Verification of accuracy by year

The level of error in the average of the 10 candidate values for maximum wind speed against the best track is shown in Table 2. Using the technique for TRMM/TMI imagery, Hoshino modified the parameters to calculate the 10 candidate values for maximum wind speed for Aqua/AMSR-E images, but the research and the algorithm using Aqua/AMSR-E imagery were based on data from 2002 through 2004. In addition, verification was performed using partial data for 2005, so 2006 figures represented independent verification data in this research. As shown in Table 2, a result similar to that found by Hoshino was obtained for BT_WP_Ave. For SCAT_ALL_Ave, on the other hand, the true value was taken as the maximum best track wind speed, and the level of error was greater than that seen in Hoshino's result using the maximum QuikSCAT/SeaWinds wind speed.

Hoshino and Nakazawa (2007) selected the maximum QuikSCAT/SeaWinds wind speed within three degrees of latitude from the TC center and made this the maximum wind speed. As seen so far, the best track maximum wind speed is obtained as the true value, so SCAT_ALL_Ave has a lower correlation than BT_WP_Ave and a greater RMSE. Henceforth, only the comparison between maximum best track wind speed and BT_WP_Ave is to be verified.

Additionally, the number of cases for 2004 (29 TCs) is considered to have been greater than those in other years because 2003 included only cases from June onward, and fewer (23) TCs were recorded for 2005 and 2006 (average value: 26.7 for 1971 – 2000 according to the Japan Meteorological Agency).

Table 2 Accuracy verification results

RMSE of individual years and for overall data (top)

RMSE of Hoshino’s research (bottom; SCAT_ALL_Ave is compared with the maximum wind speed of QuikSCAT data.)

| RMSE (m/s) | BT_WP_Ave (no. of cases) | SCAT_ALL_Ave (no. of cases) |
|-------------|--------------------------|-----------------------------|
| 2003 | 5.85 (50) | 9.65 (49) |
| 2004 | 5.22 (189) | 8.07 (188) |
| 2005 | 5.34 (116) | 8.36 (116) |
| 2006 | 6.03 (115) | 8.34 (118) |
| 2003 – 2006 | 5.55 (470) | 8.39 (471) |

| RMSE (m/s) | BT_WP_Ave | SCAT_ALL_Ave |
|-------------|-----------|--------------|
| 2002 – 2004 | 5.12 | 6.20 |
| 2005 | 5.15 | 5.18 |

(Total number of cases in the lower table: western North Pacific best track data 351; QuikSCAT data 502)

3.5 Effects of subordinate and independent data

As outlined in Section 3.4, the difference between subordinate data (2003 – 2005) and independent data (2006) in terms of RMSE is some 0.5 m/s. Little difference is found by comparing scatter diagrams between 2004 and 2006 (Figure 6), indicating that the independent 2006 data yield a similar level of calculation accuracy. The correlation coefficients between the best track maximum wind speed and BT_WP were 0.86 for 2004 and 0.81 for 2006.

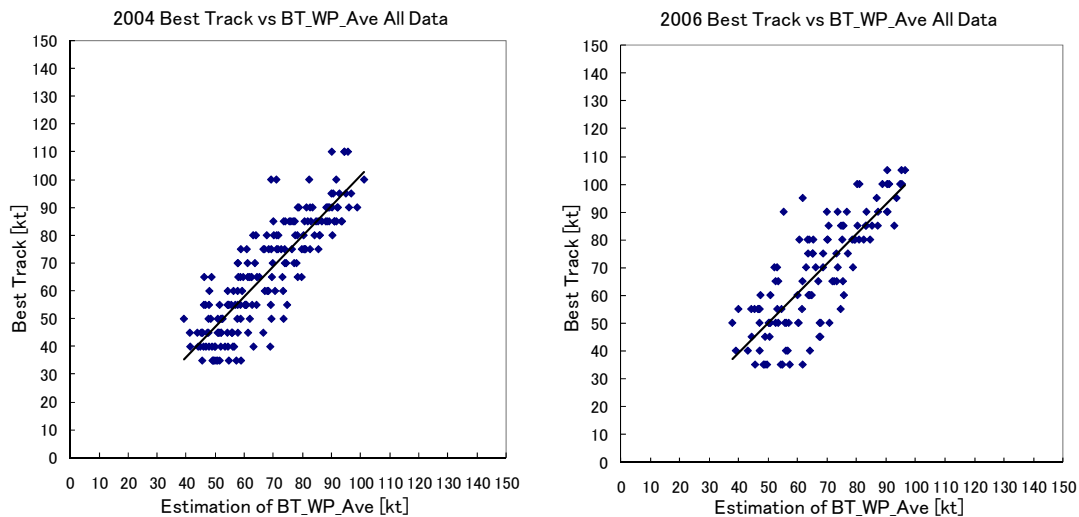


Figure 6 Scatter diagram of best track maximum wind speed and BT_WP for 2004 (left) and 2006 (right). The straight line in each figure is the regression line.

3.6 Differences in cloud patterns and TC comparison among life stages

As shown in Figure 2, if an area of high (low) brightness temperature is surrounded more than halfway around by a ring of low (high) brightness temperature in an 89 GHz (36 GHz) image, it is regarded as an MW EYE pattern from among the TC center estimation patterns of microwave imagery (the area of high [low] brightness temperature looks darker [brighter] in the image of Figure 3). Of these MW EYE patterns, those with a complete ring around the TC eye in images at 89 GHz or 36 GHz are defined as MW TEYE for further segmentation, and the effect caused by the difference in form (pattern) was checked (Figure 7). The results showed that the correlation coefficient between the best track maximum wind speed and BT_WP_Ave was 0.76 for the MW EYE pattern and 0.75 for the MW TEYE pattern, indicating that there was no improvement of accuracy from the segmentation and that the correlation coefficient was almost the same.

The accuracy of BT_WP_Ave classified* into TC life stages (developing, mature and weakening) is shown in Table 3. Classification of TC cloud patterns using the Dvorak method is also shown in Table 4. In determining criteria for the three classifications (Table 3) of developing stage, mature stage and weakening stage, maximum wind speeds of 64 KT or more (the wind speed regarded as “Typhoon” in the TC classification and equivalent to a maritime typhoon warning) or a TC cloud pattern of Eye or Banding Eye according to the Dvorak method (Table 4) were considered to represent the mature stage. Excluded from the mature stage are storms with maximum wind speeds of less than 64 KT. The developing stage is when the T number is equivalent to the CI number (corresponding to the stages of generation to development according to the Dvorak method’s classification), and the weakening stage is when the T number is different from the CI number. The T number is an index indicating TC intensity as obtained from analysis of satellite images according to the Dvorak method, and is adjusted to the CI number. When a TC is developing or has redeveloped, the T number is equivalent to the CI number. That is, the developing stage also includes times when the TC has redeveloped.

As seen in Table 3, the average error between the best track maximum wind speed and BT_WP_Ave in the developing stage is calculated with the best track maximum wind speed stronger, at +4.98 m/s, and the average error of the mature stage is calculated with the best track maximum wind speed weaker, at -1.95 m/s. Better accuracy is seen in the weakening stage than in the other stages.

Figure 8 is a scatter diagram color-coded by the life stages (developing, mature and weakening) outlined in Table 3 and by the TC cloud patterns according to the Dvorak method shown in Table 4. It indicates that there are many instances of Cb Cluster or Curved Band in the developing stage, and that BT_WP_Ave tends to be calculated as stronger than the best track maximum wind speed. In the mature stage, BT_WP_Ave corresponds closely to the best track maximum wind speed, but may be calculated as weaker for the Eye type. Cases with large margins of error are verified in Section 3.11. For the weakening stage, there are many instances of Shear/LCV or Curved Band, and the value calculated is almost the same as the best track maximum wind speed.

* Classification by setting the three TC life stages (developing, mature and weakening) as criteria was implemented to prevent cloud patterns from being included in multiple life stages when the Dvorak method’s TC life stages are used.

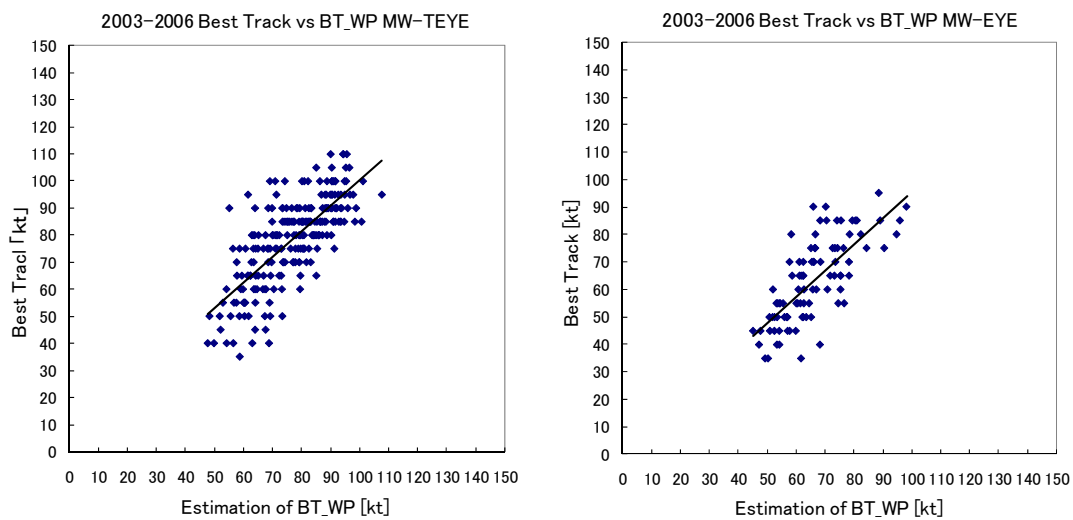


Figure 7 Scatter diagram of best track maximum wind speed and BT_WP_Ave for the microwave imagery TC cloud pattern of MW TEYE (left) and BT_WP_Ave for MW EYE (right) (MW EYE does not include MW TEYE cases.)

The straight line in each figure is the regression line.

Table 3 Accuracy of BT_WP_Ave classified by TC life stage (developing: upper left; mature: upper right; weakening: lower left) (The total number of cases from the developing stage to the weakening stage is 469. There was only one case in which TC analysis was not conducted by the satellite during the target time.)

| TC life stage | No. of data | Average of best track maximum wind speed (KT) | Average of BT_WP_Ave (KT) | Average margin of error (m/s) | RMSE (KT) | RMSE (m/s) |
|---------------|-------------|---|---------------------------|-------------------------------|-----------|------------|
| Developing | 127 | 47.28 | 56.97 | 4.98 | 12.84 | 6.60 |
| Mature | 262 | 81.35 | 77.56 | -1.95 | 10.37 | 5.33 |
| Weakening | 80 | 50.25 | 52.18 | 0.99 | 8.28 | 4.26 |
| ALL_DATA | 470 | 66.77 | 67.61 | 0.43 | 10.78 | 5.55 |

Table 4 Cloud patterns for TC center estimation using the Dvorak method and their characteristics
 (Source: Analysis and use of meteorological satellite images: Tropical cyclones)

| Stage | Cloud pattern | Cloud pattern in typhoon center | Cloud pattern characteristics |
|--------------------|---------------|---------------------------------|--|
| Generating | Cb Cluster | Unorganized Cb Cluster | Cb clusters are scattered around the center. |
| | | Organized Cb Cluster | Cb clusters are organized, and transformation to a band pattern is seen. |
| | LCV | LCV or Shear | Low-level cloud vortex |
| | Shear | | Appears when the vertical shear of the wind is greater and the dense cloud area deviates from the center determined by the low-level cloud line. |
| Developing | Curved Band | Curved Band | There is a cloud band with a curvature factor suggesting the location of the center. |
| | CDO | Distinct CDO | An almost-circular dense cloud area (CDO: central dense overcast) surrounds the center with at least one end having a clear edge. |
| | | Indistinct CDO | The CDO boundary is ragged or indistinct. |
| | Mature | Eye | Distinct Small Eye |
| Distinct Large Eye | | | Eye with a diameter greater than 40 km |
| Ragged Eye | | | The cloud walls forming the eye are either irregularly shaped or include other clouds. |
| Banding Eye | | Banding Eye | There is more than one cloud band fully surrounding the eye. |
| Weakening | Curved Band | Curved Band | There is a cloud band with a curvature factor suggesting the location of the center. |
| | Shear | LCV or Shear | Appears when the vertical shear of the wind is greater and the dense cloud area deviates from the center determined by the low-level cloud line. |
| | LCV | | Low-level cloud vortex |
| | EXL | | Transformation to an extratropical cyclone |

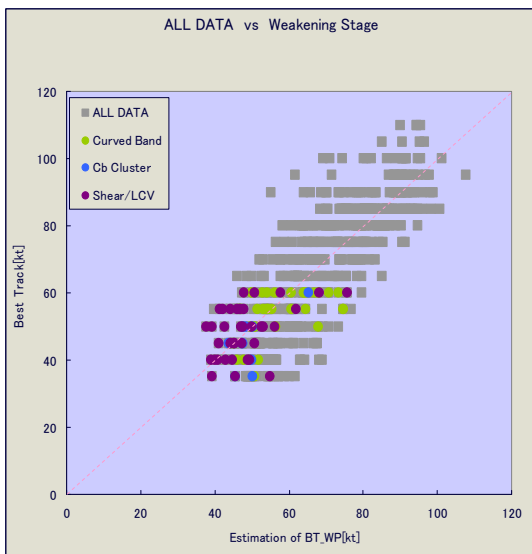
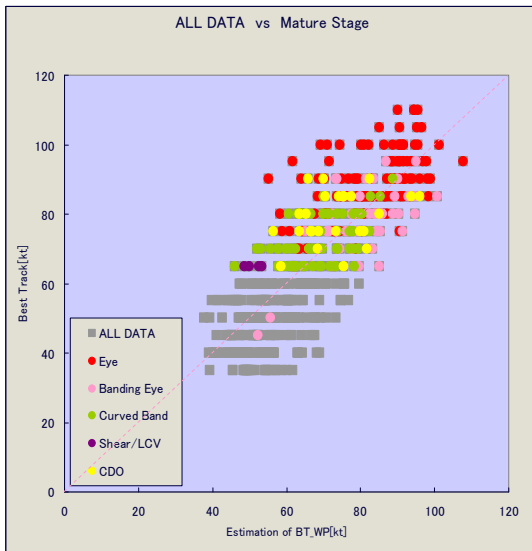
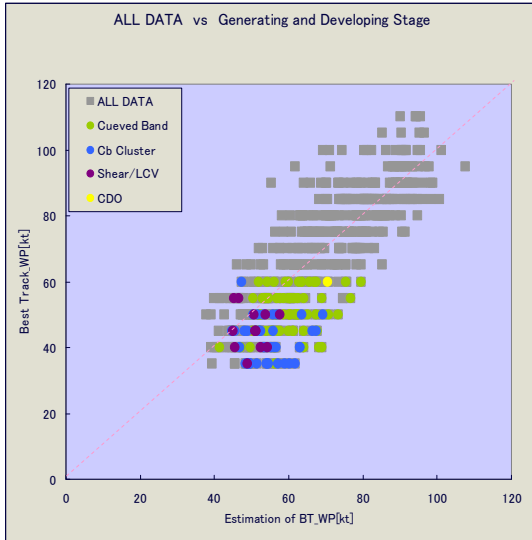


Figure 8
 Scatter diagrams of TC cloud patterns according to the classification of Table 3 (top: best track maximum wind speed and BT_WP_Ave in the developing stage; middle: best track maximum wind speed and BT_WP_Ave in the mature stage; bottom: best track maximum wind speed and BT_WP_Ave in the weakening stage. Explanatory notes are shown in each figure [“Eye,” etc. are as per Dvorak cloud pattern classification]. To facilitate understanding of the correlation tendency, the best track maximum wind speed, or BT_WP_Ave, is indicated with dashed lines.)

3.7 Correlation between best track maximum wind speed and BT_WP for TC cloud patterns in microwave images

For each microwave image TC cloud pattern, the correlation between the best track maximum wind speed and the BT_WP of the 10 candidate values for maximum wind speed and RMSE was ascertained (Figure 9).

As detailed in Section 3.6, the correlation between MW EYE and MW TEYE was nearly identical in these TC cloud patterns, but on the basis of the 10 candidate values for maximum wind speed, the sixth maximum wind speed value (V6) of MW TEYE had a higher correlation than any of the maximum wind speed values for the MW EYE patterns. Conversely, the second and seventh had lower correlations than any maximum wind speed value. Additionally, MW SHEAR and MW BAND showed low correlations for the sixth maximum wind speed value, while the RMSE was high. A difference is thus seen in the regression formula that shows the maximum wind speed with a high correlation to known data according to the analysis pattern. For BT_WP_Ave, the correlation is the highest with MW EYE and MW TEYE, followed by MW SHEAR, while that for MW BAND is low.

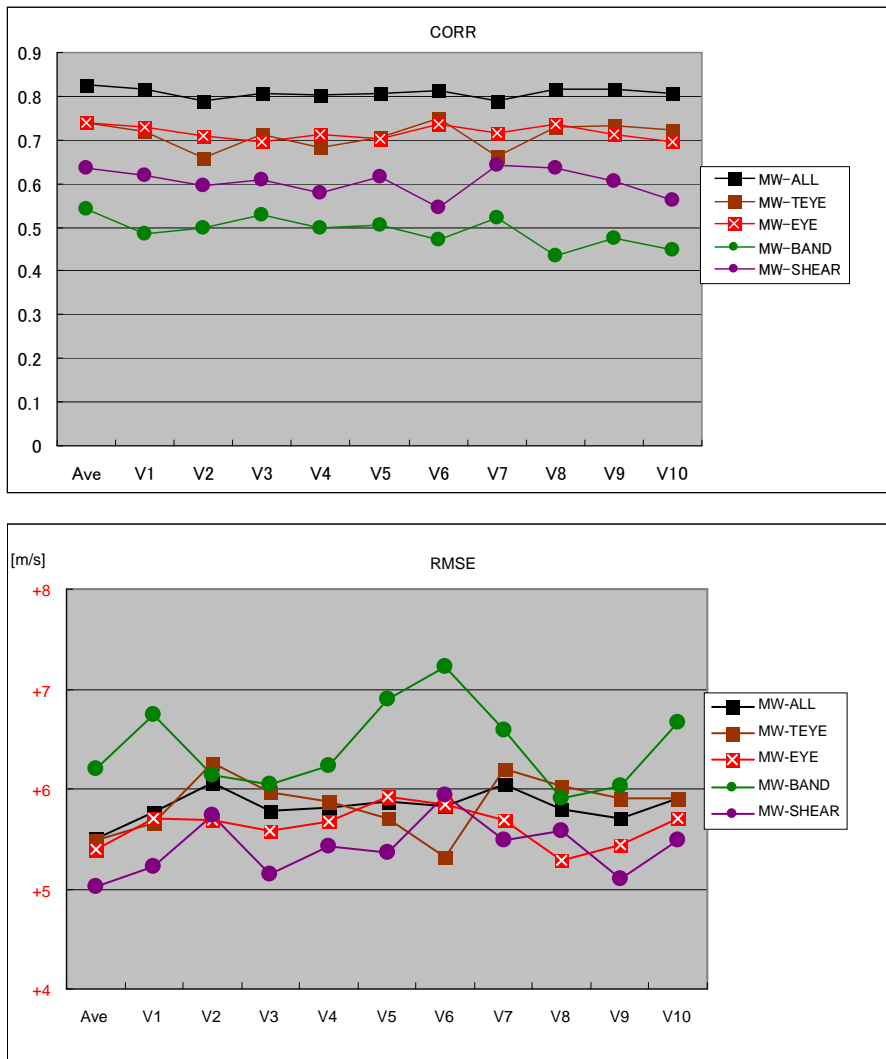
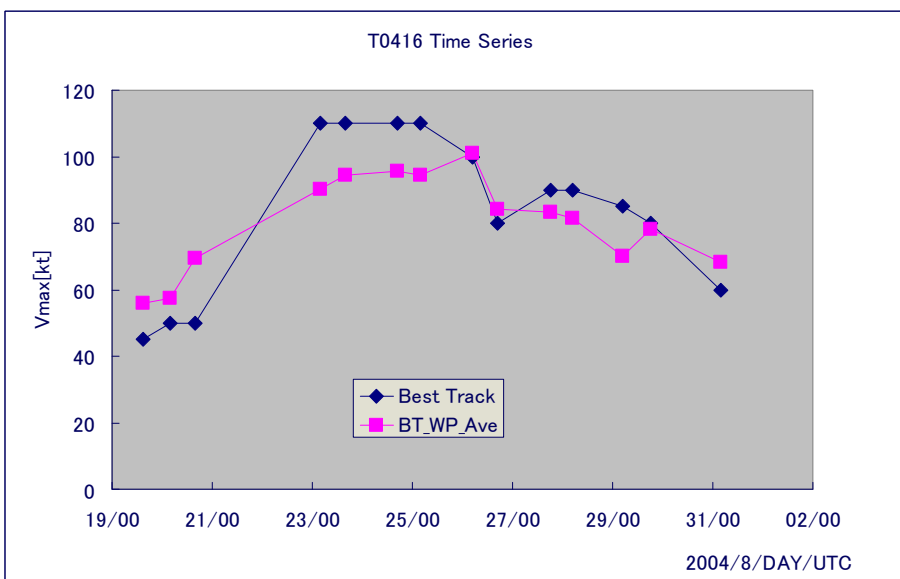
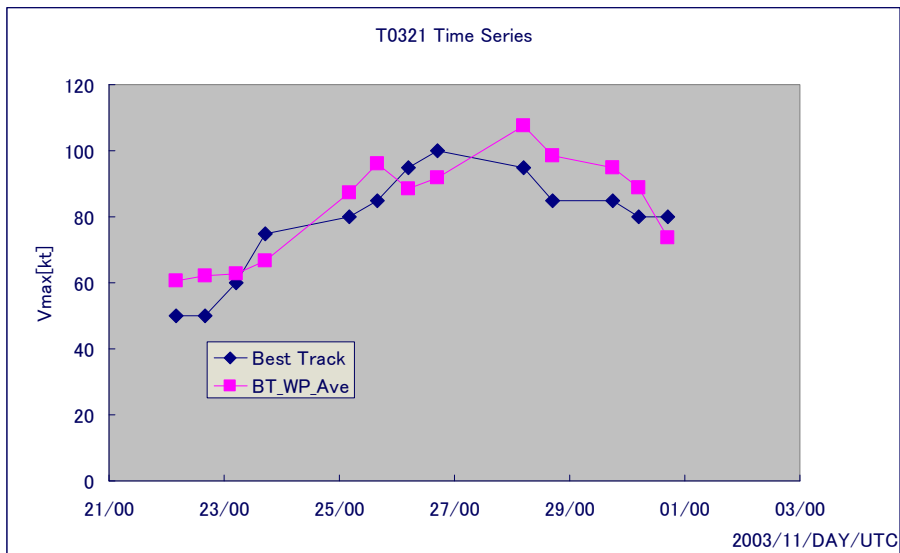


Figure 9 Correlation between best track maximum wind speed and candidate values for the respective maximum wind speeds of BT_WP (top) and RMSE (bottom) (ALL in the figure indicates all patterns. V1 to V10 are the candidate values for the maximum wind speed [Vmax], and Ave is their average.)

3.8 Comparison of time changes in maximum wind speed

An example of checked time changes for the best track maximum wind speed and BT_WP_Ave is shown in Figure 10. Time not captured in Aqua/AMSR-E images cannot be compared and only a part of whole TC life stages can be seen, but on the whole, BT_WP_Ave is calculated as stronger in the early stages of development as compared with the best track maximum wind speed. The calculated increase in wind speed is moderate, however, and toward the mature stage, the results adversely tend to be slightly weaker as compared with the best track maximum wind speed. On the other hand, BT_WP_Ave is calculated with good correspondence in the weakening stage when the best track maximum wind speed weakens, in a similar fashion to the results outlined in 3.7. While

there is a margin of error in the strength from the beginning of the developing stage toward the mature stage, the trend of change shows good correspondence.



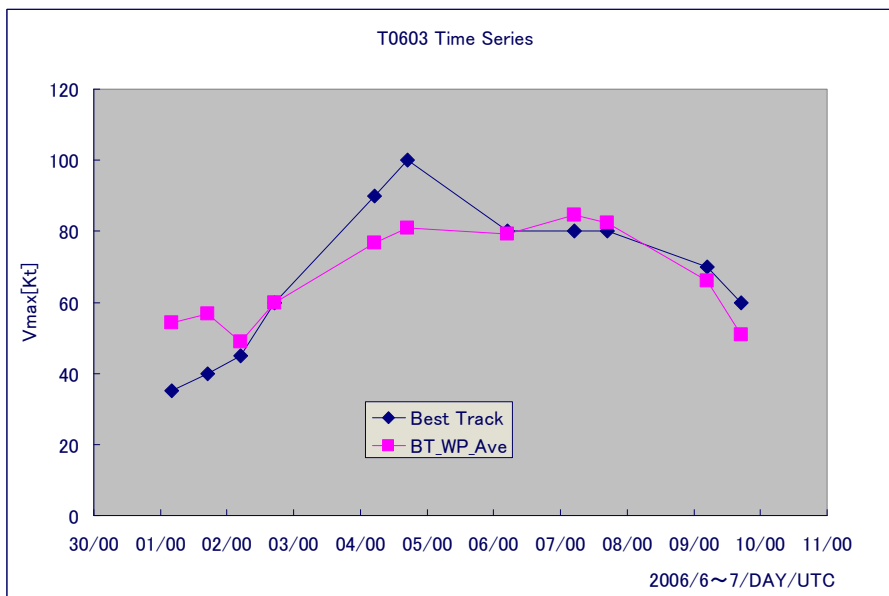
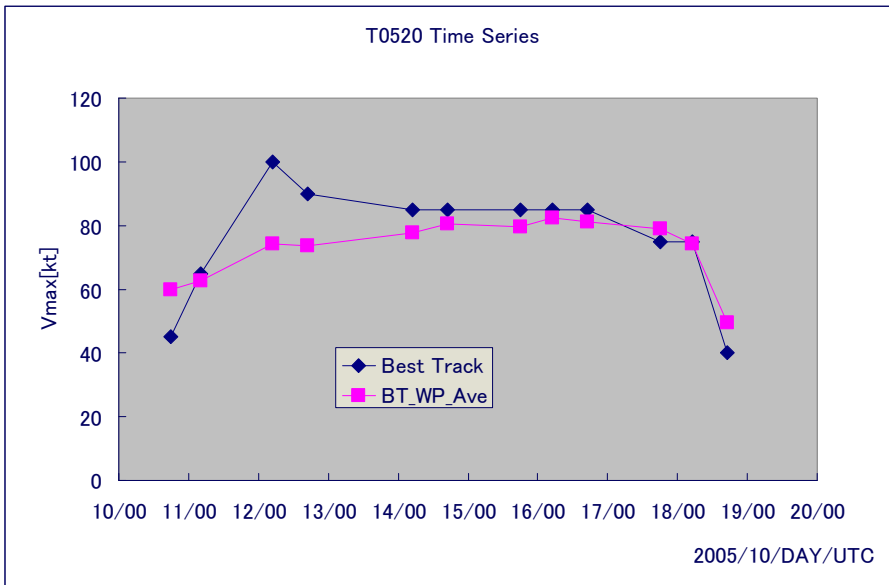


Figure 10 Comparison of time changes between best track maximum wind speed and BT_WP_Ave (from the top: T0321, T0416, T0520 and T0603)

3.9 Comparison of each best track maximum wind speed with BT_WP_Ave

As can be seen from Figure 10, at the beginning of the developing stage, BT_WP_Ave is calculated as stronger than the best track maximum wind speed, but from around 60 KT to 80 KT, the best track maximum wind speed tends to be stronger. Referring to this tendency, statistical research was conducted using the classes of best track maximum wind speed shown in Table 5.

The RMSE is at its smallest when the best track maximum wind speed is from 70 to 79 KT. A large RMSE is seen up to 49 KT and from 90 to 110 KT, and a high positive bias is seen up to 49 KT with a high negative bias from 90 to 110 KT. Additionally, a reversal of positive and negative figures in the average margin of error takes place with a boundary of around 70 KT, indicating that best track maximum wind speeds stronger than this tend to yield a negative bias. This matches the comparison by life stage in Section 3.6 and the results of time change comparison in Section 3.8.

Table 5 Comparison of BT_WP_Ave accuracy by class of best track maximum wind speed

| | No. of cases | Average of best track maximum wind speed (KT) | Average of BT_WP_Ave (KT) | Average margin of error (m/s) | RMSE (KT) | RMSE (m/s) |
|-------------|--------------|---|---------------------------|-------------------------------|-----------|------------|
| ALL_DATA | 470 | 66.77 | 67.61 | 0.43 | 10.78 | 5.55 |
| Up to 49 KT | 95 | 41.00 | 51.92 | 5.62 | 13.40 | 6.89 |
| 50 – 59 KT | 83 | 52.35 | 55.86 | 1.80 | 9.23 | 4.75 |
| 60 – 69 KT | 62 | 62.42 | 63.48 | 0.55 | 9.01 | 4.64 |
| 70 – 79 KT | 67 | 72.76 | 71.50 | -0.65 | 8.57 | 4.41 |
| 80 – 89 KT | 90 | 82.72 | 79.95 | -1.42 | 8.71 | 4.48 |
| 90 – 110 KT | 73 | 95.21 | 86.08 | -4.70 | 13.70 | 7.05 |

3.10 Effect of rapid TC development or weakening on BT_WP_Ave

As mentioned in Section 2.2, the observation time difference between Aqua/AMSR-E imagery and the best track is three hours at most. Verification was performed to ascertain whether this time difference would have an effect in cases of rapid TC development or weakening. The correlation was checked with the exclusion of any values observed during periods when the change in the MET Number (Model Expected T Number) in the past 24 hours was ± 1.5 as analyzed by the Dvorak method (Table 6). The MET Number is an index used in the Dvorak method to show the present strength of a TC by comparing a current image of it with one from 24 hours earlier and judging the related development or weakening. For the amount of change in the past 24 hours, 1.0 is added (deducted) in the case of standard development (weakening), and 1.5 is added (deducted) in the case of rapid (slow) development. That is, if the amount of change in the MET Number in the past 24 hours is +1.5, the TC is rapidly developing, while a value of -1.5 represents rapid weakening.

The results show that the correlation coefficient became slightly higher (to 0.85 from 0.83 in the overall data), and that the RMSE also improved slightly (to 5.41 m/s from 5.55 m/s in the overall data).

Table 6 Comparison of BT_WP_Ave accuracy upon rapid development/weakening in terms of MET Number change in the past 24 hours

| | No. of cases | Average of best track maximum wind speed (KT) | Average of BT_WP_Ave (KT) | Correlation | Average margin of error (m/s) | RMSE (KT) | RMSE (m/s) |
|--|--------------|---|---------------------------|-------------|-------------------------------|-----------|------------|
| ALL_DATA | 470 | 66.77 | 67.61 | 0.83 | 0.43 | 10.78 | 5.55 |
| Excluding the MET Number change in the past 24 hours = ± 1.5 | 361 | 66.87 | 68.42 | 0.85 | 0.80 | 10.52 | 5.41 |

3.11 Cases with large errors

The difference between the best track maximum wind speed and BT_WP_Ave was ascertained, and cases with a large difference (i.e., a bias of ± 20 KT or more) are shown in Table 7.

Hoshino and Nakazawa (2007) used parameters of high correlation with the best track maximum wind speed and selected 10 regression formulas for small RMSEs from among many parameter combinations. It is therefore not easy to explain the cause of higher bias from formulas created by combinations of various parameters. Consequently, in the frequency band where images can be displayed with the GMSLPM/SATAID analytical tool, comparison was made of images with the parameters used frequently in the regression formula for calculating the 10 candidate values for maximum wind speed shown in Table 1-1, and their characteristics were verified.

The characteristics checked were distribution of brightness temperature (TBB) for images of 7 GHz_H, 7 GHz_V, 10 GHz_H, 19 GHz_H, 19 GHz_V, 24 GHz_H and 89 GHz_V (where V is a vertically polarized wave element and H is a horizontally polarized wave element). The results showed a clear tendency for the brightness temperature distribution of 7 GHz_H. TB07H_AREA110_C10 (the ratio of pixels for which the brightness temperature in a concentric circle with a one-degree radius from the center is 110K or more on the horizontally polarized wave of the 7 GHz band channel) is used most as a parameter, and the cause of the higher bias was verified in the two separate cases of higher positive bias and higher negative bias using the pixel ratio of 110 K or more adopted as a threshold value for this parameter.

(1) Higher positive bias

In Table 7, 17 incidences of BT_WP_Ave being calculated as more than the best track maximum wind speed by 20 KT or more (a higher positive bias) are listed, and 16 out of 17 cases appear in the developing stage when the best track maximum wind speed is 55KT or less. It should also be noted that cases of MW EYE, MW TEYE or MW BAND in the TC cloud patterns of microwave images and Curved Band or Cb Cluster in those of the Dvorak method account for more than 80% (15 out of 17 cases), and BT_WP_Ave may be calculated as higher in these cases.

Here, narrowing down further to the case of a best track maximum wind speed of 55 KT or less in the developing stage, MW TEYE or MW EYE in the TC cloud patterns of microwave images, and Curved Band or Cb Cluster in those of the Dvorak method, the corresponding figure was

found to be 8 out of 17 cases (almost half). To facilitate comparison with higher positive bias cases, a comparison was made with 9 cases of lower bias (i.e., biases of ± 5.0 KT or less were extracted) under the same conditions as these 8 cases.

AREA110_C10 (the ratio of pixels for which the brightness temperature in a concentric circle with a radius of one degree from the center is 110K or more) for incidences of higher positive bias (8 cases) was 50 to 94%, with an average of 74%. On the other hand, the same value for incidences with a smaller margin of error (9 cases) was 13 to 52%, with an average of 36% (Tables 8 and 9).

Images of higher positive bias cases are shown in Figure 11. In all incidences of higher positive bias, AREA110_C10 (the colored parts in the figures) covers nearly half of the one-degree circle at a minimum. On the other hand, in the cases of lower positive bias shown in Figure 12, AREA110_C10 is smaller – about half the size seen in Figure 11.

(2) Higher negative bias

In the cases of Table 7 where BT_WP_Ave is calculated as less than the best track maximum wind speed by 20 KT or more (a higher negative bias), MW EYE or MW TEYE in the TC cloud patterns of the microwave images and Eye in those of the Dvorak method account for most incidences (9 out of 11). Additionally, all appear in the mature stage and have the characteristic of a higher best track maximum wind speed in contrast to cases with a higher positive bias.

The top 10 cases of higher negative bias for AREA110_C10 (the ratio of pixels for which the brightness temperature in a concentric circle with a radius of one degree from the center is 110 K or more) are shown in Table 10. The top 10 cases of lower bias (either positive or negative) are shown in Table 11 among the cases with best track maximum wind speeds of 90 KT or more, because most of the cases of higher negative bias (shown in Table 10) were found when best track maximum wind speeds were 90 KT or more (MW TEYE in the TC cloud patterns of microwave images).

Figure 13 shows images of cases where the BT_WP_Ave wind speed was lower (a higher negative bias) than the best track maximum wind speed, and Figure 14 shows images of cases with a lower bias. In all cases of higher negative bias, AREA110_C10 does not fully cover the concentric circle with a one-degree radius (90% or less). On the other hand, it fully covers the circle in all cases of lower bias. AREA110_C10 shows an average of 65% (36 to 90%) for 10 cases of higher negative bias, and 100% (fully covering a concentric circle with a radius of one degree from the center) for all 10 cases of lower bias.

A trend is also seen (as shown in Figure 15) whereby smaller AREA110_C10 values are accompanied by lower BT_WP_Ave wind speed estimation, thereby making the negative bias higher.

Table 7 Cases of higher bias; large differences between best track maximum wind speed and BT_WP_Ave (bias of ± 20 KT or more)

| YYYY/MM/DD Time | Best track maximum wind speed [KT] | BT_WP_ Ave [KT] | Error [KT] | MW cloud pattern | Dvorak method cloud pattern | TC life stage |
|--------------------|---|--------------------|---------------|------------------------|-----------------------------------|------------------|
| 2004/08/28, 03 UTC | 40 | 68.9 | +28.9 | TEYE | Curved Band | Developing |
| 2005/10/29, 06 UTC | 40 | 68.3 | +28.3 | EYE | Curved Band | Developing |
| 2006/08/14, 05 UTC | 35 | 61.7 | +26.7 | EYE | Cb Cluster | Developing |
| 2003/09/06, 04 UTC | 35 | 60.2 | +25.2 | BAND | Cb Cluster | Developing |
| 2006/08/08, 18 UTC | 40 | 64.2 | +24.2 | SHEAR | Curved Band | Developing |
| 2004/06/06, 18 UTC | 35 | 58.9 | +23.9 | TEYE | Cb Cluster | Developing |
| 2004/11/17, 05 UTC | 50 | 73.5 | +23.5 | TEYE | Curved Band | Developing |
| 2004/04/05, 04 UTC | 40 | 63.2 | +23.2 | TEYE | Cb Cluster | Developing |
| 2003/09/06, 16 UTC | 40 | 63.0 | +23.0 | SHEAR | Cb Cluster | Developing |
| 2006/11/09, 17 UTC | 45 | 67.7 | +22.7 | TEYE | Curved Band | Developing |
| 2006/08/06, 04 UTC | 45 | 67.4 | +22.4 | BAND | Cb Cluster | Developing |
| 2004/05/18, 17 UTC | 35 | 57.2 | +22.2 | BAND | Cb Cluster | Developing |
| 2005/08/23, 16 UTC | 55 | 76.7 | +21.7 | EYE | Curved Band | Developing |
| 2004/08/08, 17 UTC | 45 | 66.5 | +21.5 | BAND | Cb Cluster | Developing |
| 2003/08/29, 17 UTC | 35 | 56.3 | +21.3 | BAND | Curved Band | Developing |
| 2006/08/06, 16 UTC | 50 | 70.8 | +20.8 | BAND | Curved Band | Developing |
| 2003/08/24, 19 UTC | 65 | 85.2 | +20.2 | TEYE | B-Eye | Mature |
| 2006/08/08, 18 UTC | 90 | 69.9 | -20.1 | TEYE | CDO | Mature |
| 2005/09/28, 05 UTC | 90 | 68.6 | -21.4 | TEYE | Eye | Mature |
| 2005/10/30, 19 UTC | 80 | 58.3 | -21.7 | EYE | Eye | Mature |
| 2005/06/04, 05 UTC | 95 | 71.5 | -23.5 | TEYE | Eye | Mature |
| 2005/06/04, 18 UTC | 90 | 65.9 | -24.1 | EYE | CDO | Mature |
| 2005/10/12, 05 UTC | 100 | 74.4 | -25.6 | TEYE | Eye | Mature |
| 2005/06/03, 05 UTC | 90 | 64.1 | -25.9 | TEYE | Eye | Mature |
| 2004/10/07, 18 UTC | 100 | 71.0 | -29.0 | TEYE | Eye | Mature |
| 2004/10/08, 05 UTC | 100 | 69.2 | -30.8 | TEYE | Eye | Mature |
| 2006/11/10, 17 UTC | 95 | 61.7 | -33.3 | TEYE | Eye | Mature |
| 2006/11/10, 06 UTC | 90 | 55.3 | -34.7 | TEYE | Eye | Mature |

Table 8 Cases of higher positive bias; lower BT_WP_Ave wind speed than the best track maximum wind speed (MW EYE or MW Band in the TC cloud patterns of microwave images and Curved Band or Cb Cluster in those of the Dvorak method)

| Error [KT] | Best track maximum wind speed [KT] | BT_WP_Ave [KT] | TB07H_AREA110_C10 [%] |
|------------|------------------------------------|----------------|-----------------------|
| +28.9 | 40 | 68.9 | 88 |
| +28.3 | 40 | 68.3 | 71 |
| +26.7 | 35 | 61.7 | 64 |
| +23.9 | 35 | 58.9 | 50 |
| +23.5 | 50 | 73.5 | 83 |
| +23.2 | 40 | 63.2 | 72 |
| +22.7 | 45 | 67.7 | 73 |
| +21.7 | 55 | 76.7 | 94 |
| Ave. +24.8 | Ave. 43 | Ave. 67.0 | Ave. 74 |

Table 9 Cases of lower bias; smaller differences between the best track maximum wind speed and the BT_WP_Ave wind speed (MW EYE or MW BAND in the TC cloud patterns of microwave images and Curved Band or Cb Cluster in those of the Dvorak method)

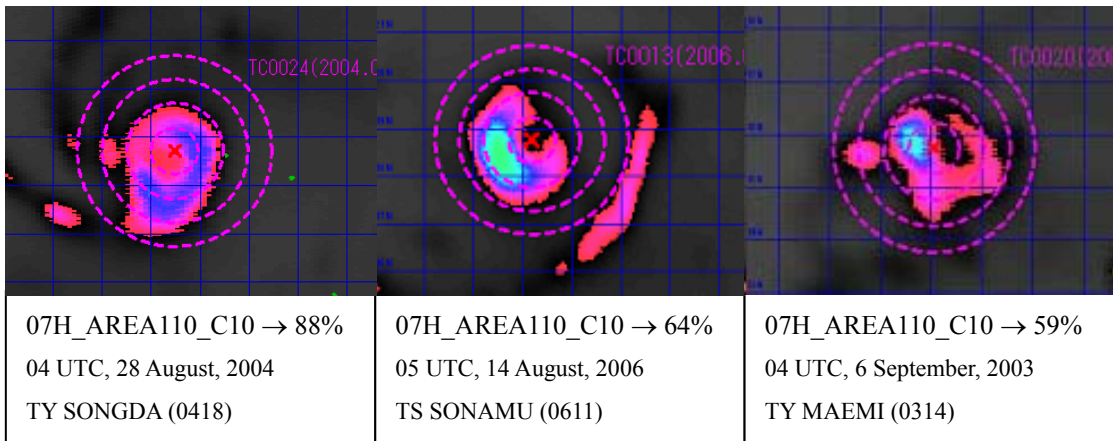
| Error [KT] | Best track maximum wind speed [KT] | BT_WP_Ave [KT] | TB07H_AREA110_C10 [%] |
|------------|------------------------------------|----------------|-----------------------|
| +1.8 | 50 | 51.8 | 28 |
| +2.0 | 50 | 52.0 | 43 |
| +2.5 | 50 | 52.5 | 33 |
| +3.4 | 50 | 53.4 | 42 |
| -1.8 | 55 | 53.2 | 52 |
| -1.4 | 55 | 53.6 | 42 |
| -0.8 | 55 | 54.2 | 13 |
| +1.9 | 55 | 56.9 | 31 |
| +2.7 | 55 | 57.7 | 40 |
| Ave. +1.1 | Ave. 53 | Ave. 54.0 | Ave. 36 |

Table 10 Cases of higher negative bias; lower BT_WP_Ave wind speed than the best track maximum wind speed

| Error [KT] | Best track maximum wind speed [KT] | BT_WP_Ave [KT] | TB07H_AREA110_C10 [%] |
|------------|------------------------------------|----------------|-----------------------|
| -34.7 | 90 | 55.3 | 36 |
| -33.3 | 95 | 61.7 | 60 |
| -30.8 | 100 | 69.2 | 66 |
| -29.0 | 100 | 71.0 | 70 |
| -25.9 | 90 | 64.1 | 56 |
| -25.6 | 100 | 74.4 | 90 |
| -24.1 | 90 | 65.9 | 68 |
| -23.5 | 95 | 71.5 | 74 |
| -21.7 | 80 | 58.3 | 55 |
| -21.4 | 90 | 68.6 | 80 |
| Ave. -27.0 | Ave. 93 | Ave. 66.0 | Ave. 65 |

Table 11 Cases of lower bias; smaller difference between the best track maximum wind speed and the BT_WP_Ave wind speed (best track maximum wind speed of 90 KT or more)

| Error [KT] | Best track maximum wind speed [KT] | BT_WP_Ave [KT] | TB07H_AREA110_C10 [%] |
|------------|------------------------------------|----------------|-----------------------|
| +1.6 | 90 | 91.6 | 100 |
| +1.2 | 100 | 101.2 | 100 |
| +0.6 | 90 | 90.6 | 100 |
| +0.4 | 90 | 90.4 | 100 |
| +0.2 | 90 | 90.2 | 100 |
| -0.1 | 95 | 94.9 | 100 |
| -0.7 | 90 | 89.3 | 100 |
| -1.2 | 90 | 88.8 | 100 |
| -1.3 | 90 | 88.7 | 100 |
| -1.4 | 95 | 93.6 | 100 |
| Ave. -0.1 | Ave. 92 | Ave. 91.9 | Ave. 100 |



[Brightness temperature gradation] (values of less than 110K are indicated in grayscale)

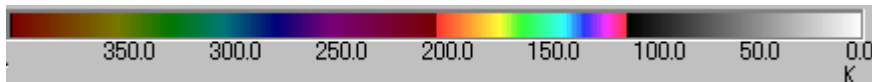


Figure 11 Sample images of a horizontally polarized wave on the 7 GHz band channel in the case of the higher positive bias shown in Table 8 (The dashed lines are concentric circles with radii increasing in increments of 0.5 degrees from the center. The area of the concentric circle with a radius of 1 degree from the center is C10. Colored areas indicate brightness temperatures of 110 K or more.)

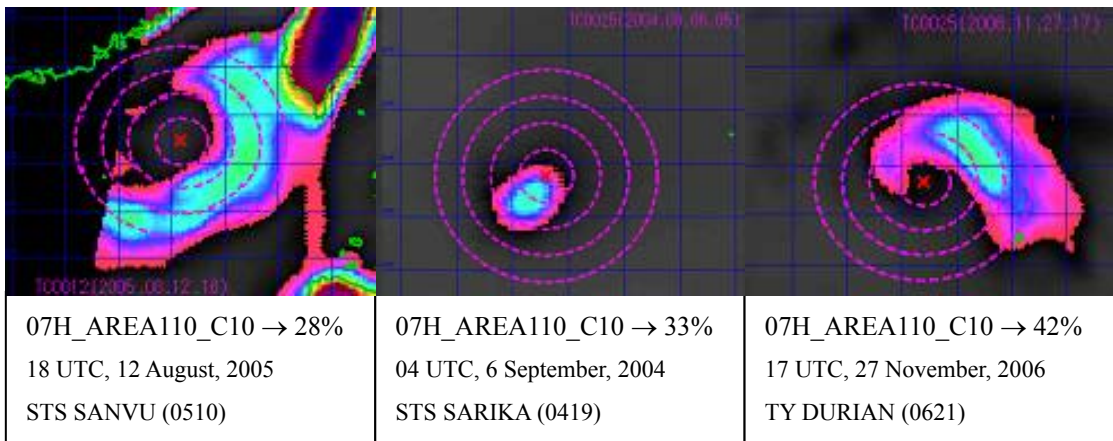


Figure 12 Sample images of a horizontally polarized wave on the 7 GHz band channel in the case of the lower bias shown in Table 9 (display elements and color scale as per those for Figure 11)

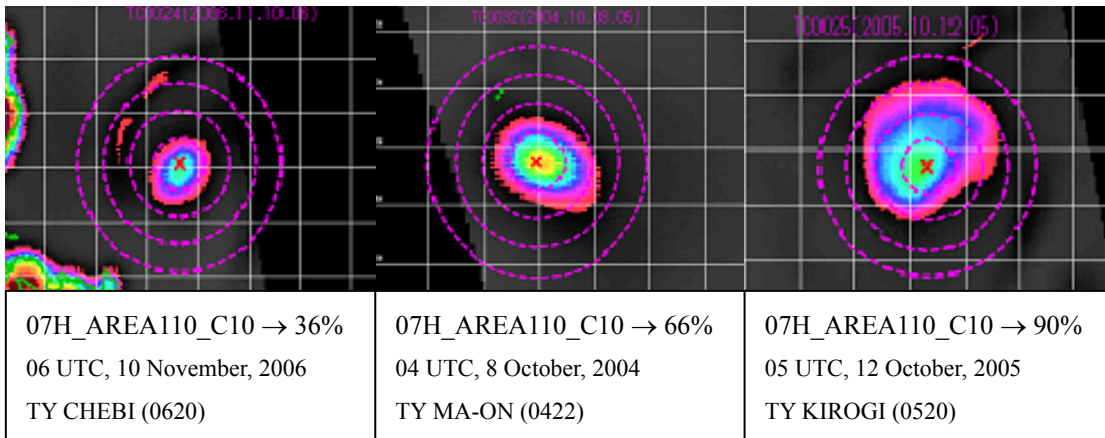


Figure 13 Sample images of a horizontally polarized wave on the 7 GHz band channel in the case of the higher negative bias shown in Table 10 (display elements and color scale as per those for Figure 11)

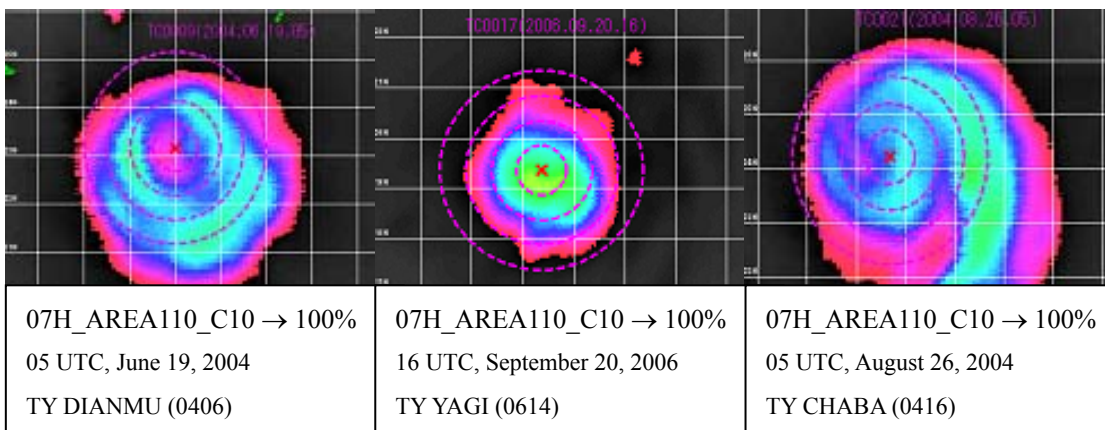


Figure 14 Sample images of a horizontally polarized wave on the 7 GHz band channel in the case of the lower bias shown in Table 11 (display elements and color scale as per those for Figure 11)

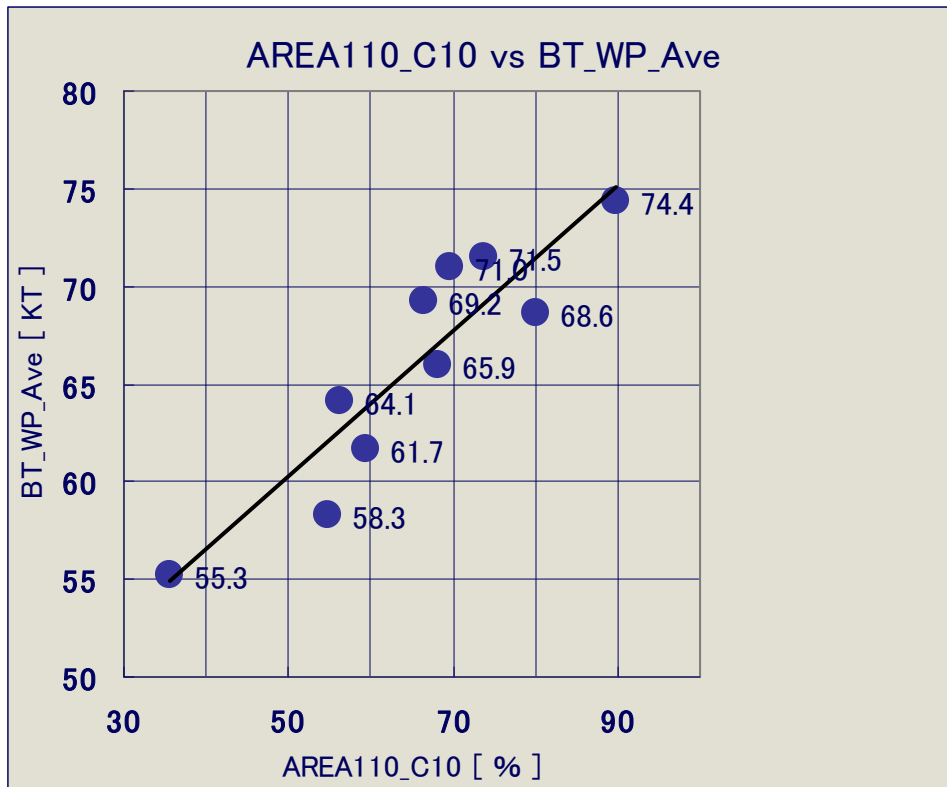


Figure 15 Scatter diagram of AREA110_C10 (horizontally polarized wave on the 7 GHz band channel) and BT_WP_Ave (figures in the graph are BT_WP_Ave [KT])
The straight line in the figure is the regression line.

3.12 Summary of verification results

The verification results obtained from this research are summarized below. (The results pertain to BT_WP_Ave [data from 2003 to 2006], thereby eliminating the effect of land.)

- (1) The correlation coefficient between the best track maximum wind speed and BT_WP_Ave was high at 0.83. This was the same as the trend seen in verification by year, and a similarly high correlation was observed irrespective of whether the data were subordinate or independent.
- (2) The results of accuracy verification for the best track maximum wind speed and BT_WP_Ave from various perspectives are outlined below.
 - (i) Comparison by TC life stage (developing, mature and weakening) showed that BT_WP_Ave is calculated as stronger than the best track maximum wind speed in the developing stage, and that many of the cloud patterns of the Dvorak method are Cb Cluster or Curved Band. In the mature stage, the best track maximum wind speed and BT_WP_Ave correspond closely, but in the cases of the Eye pattern of the Dvorak method, BT_WP_Ave may be calculated weaker than the best track maximum wind speed. In the weakening stage, the level of error tends to be smaller than in the development or mature stages, and Shear or Curved Band is mostly seen in terms of the cloud patterns of the Dvorak method.

- (ii) In comparison by TC cloud patterns for microwave images, BT_WP_Ave showed the highest correlation in MW EYE or MW TEYE, followed by MW SHEAR. MW BAND gives the lowest correlation.
- (iii) As outlined in Section 3.10, BT_WP_Ave tends to show a worse correlation when the TC is either rapidly developing or rapidly weakening.
- (iv)-(1) A case in which the calculated BT_WP_Ave value showed a high positive bias (calculated as at least 20 KT higher) appeared in the developing stage when the best track maximum wind speed was 55 KT or less, and cases of MW EYE, MW TEYE or MW BAND in the TC cloud patterns of microwave images and Curved Band or Cb Cluster in those of the Dvorak method accounted for more than 80% of the total. About half the cases of higher positive bias were found when the best track maximum wind speed was 55 KT or less in the developing stage and in cases of MW TEYE or MW EYE in the TC cloud patterns of microwave images and Curved Band or Cb Cluster pattern in those of the Dvorak method. When compared with cases of lower bias (with biases of ± 5.0 KT or less extracted) under the same conditions, AREA110_C10 of all higher positive bias cases generally covered more than half of the one-degree circle. On the other hand, its size in lower positive bias cases was reduced to about half that seen in higher positive bias cases.
- (iv)-(2) Of the cases in which the calculated BT_WP_Ave showed a high negative bias (calculated as at least 20 KT lower), MW EYE or MW TEYE in the TC cloud patterns of microwave images and Eye in those of the Dvorak method accounted for the majority (9 cases out of 11), all appeared in the mature stage with the characteristic of a higher best track maximum wind speed than the higher positive bias cases of (iv)-(1), and the best track maximum wind speed was 90 KT or more in 10 out of 11 higher negative bias cases. Comparison with 10 lower bias cases in incidences of a best track maximum wind speed of 90 KT or more showed that all the lower bias cases had 100% AREA110_C10 coverage, whereas in all the higher negative bias cases, AREA110_C10 did not fully cover the one-degree concentric circle, with an average coverage of 65%. Additionally, the wind speed of BT_WP_Ave was estimated as lower for smaller AREA110_C10 sizes, thus highlighting the trend of higher negative bias.

4. Consideration

- (1) In accuracy verification by TC cloud patterns of microwave images, the causes for the lowest correlation of MW BAND were reviewed. As seen from Table 12, if the TC cloud pattern of microwave imagery is MW BAND, the emergence frequency of Curved Band or Cb Cluster in those of the Dvorak method approaches 70%. As seen from Table 4, Curved Band or Cb Cluster in the cloud patterns of the Dvorak method is likely to appear in the generating stage or the developing stage, and has no eye or low-level cloud vortex to clearly suggest the location of the center. Determining the center position in such cases lacks accuracy because it is taken as the center of the curvature factor or the emergence point of convective cloud lines pointing to the center, which can be considered multiple. This is seen as one of the reasons for the lower level of accuracy in determining the center position and for the higher level of error as compared to other

TC cloud patterns of microwave images. Additionally, the presence of convective clouds near the center even without strong winds could make the calculated BT_WP value higher and increase the level of error.

The frequent appearance of MW BAND in the TC cloud patterns of microwave images in the generating stage or the developing stage and the higher calculated BT_WP value correspond to the verification result showing that BT_WP_Ave is calculated as stronger when the best track maximum wind speed is low (in the generating or developing stages of the Dvorak method).

- (2) As better accuracy is seen in the TC weakening stage, analysis results with a higher level of objectivity can be obtained by referring to BT_WP_Ave when TC cloud patterns of the Dvorak method are not clear in the weakening stage.
- (3) The verification result of BT_WP_Ave showing a high positive bias (calculated as at least 20 KT higher than the best track value) or a high negative bias (calculated as at least 20 KT lower than the best track value) indicates that TB07H_AREA110_C10 (the ratio of pixels for which the brightness temperature in a concentric circle with a one-degree radius from the center is 110K or more on the horizontally polarized wave of the 7 GHz band channel) can be used for effective judgment in cases with large errors.

To calculate the 10 candidate values for maximum wind speed, various combinations of parameters are used to create a regression formula. Although it is difficult to determine the cause of the significant divergence from TB07H_AREA110_C10 only, a judgment factor can be obtained.

- (4) Usage in actual operation is considered from the verification results. As analytical results according to the Dvorak method are generally relied on in typhoon intensity analysis, the flowchart in Figure 16 was prepared using the relationship between the Dvorak method CI number and the maximum wind speed (as shown in Table 13) as well as by considering the TC life stage. As mentioned earlier, the CI number of the Dvorak method is equivalent to the T number in the TC generating and developing stages.

As seen from the above, TC intensity estimation with a higher level of accuracy can be expected by adding intensity estimation from microwave imagery to intensity analysis using the conventional Dvorak method.

Table 12 Emergence frequency of visible and infrared (IRVIS) cloud patterns and microwave (MW) analytical cloud patterns in the Dvorak method (from Nishimura et al. [2007])
(MW EYE includes the MW TEYE instances in this research.)

| | IRVIS Curved Band | IRVIS Banding Eye | IRVIS Embedded | IRVIS Eye | IRVIS Shear | IRVIS Cb-Cluster |
|----------|-------------------|-------------------|----------------|-----------|-------------|------------------|
| MW SHEAR | 3.5 | 4.8 | 0.0 | 0.0 | 71.4 | 22.7 |
| MW EYE | 64.9 | 95.2 | 100.0 | 100.0 | 14.3 | 40.9 |
| MW BAND | 31.6 | 0.0 | 0.0 | 0.0 | 14.3 | 36.4 |

(%)

Table 13 Relationship between the Dvorak method CI number and maximum wind speed in the western North Pacific (Koba et al. [1990])

| CI number | Maximum wind speed (KT) |
|-----------|-------------------------|
| 1.0 | 22 |
| 1.5 | 29 |
| 2.0 | 36 |
| 2.5 | 43 |
| 3.0 | 50 |
| 3.5 | 57 |
| 4.0 | 64 |
| 4.5 | 71 |
| 5.0 | 78 |
| 5.5 | 85 |
| 6.0 | 93 |
| 6.5 | 100 |
| 7.0 | 107 |
| 7.5 | 115 |
| 8.0 | 122 |

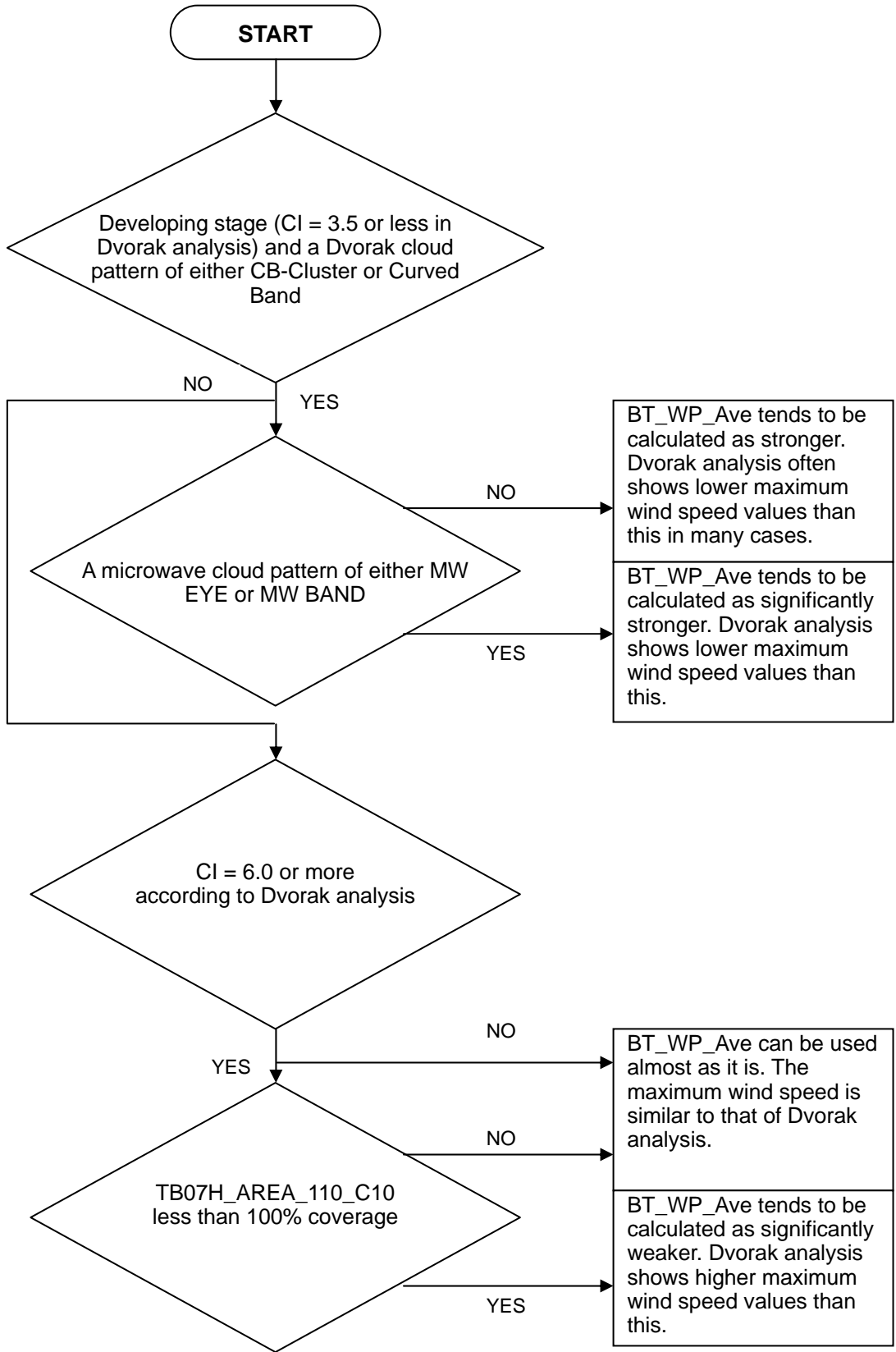


Figure 16 Flowchart for operational use

5. Conclusion

Using the Aqua/AMSR-E version of TC intensity estimation according to the technique of Hoshino and Nakazawa (2007), comparison was made between the average of 10 candidate values for maximum wind speed and the best track maximum wind speed value. The results indicated that independent data showed a high correlation similar to that of subordinate data.

From the perspective of TC life, in the developing stage (corresponding to the stages of generating to developing in the Dvorak method), BT_WP_Ave tends to be calculated as stronger than the best track maximum wind speed, and Cb Cluster or Curved Band in the cloud patterns of the Dvorak method often appears. Furthermore, in cases where the TC cloud patterns of microwave images were MW EYE, MW TEYE or MW BAND, BT_WP_Ave was calculated as significantly stronger. In the mature stage, the RMSE and average error became smaller and corresponded more closely to the best track, but BT_WP_Ave was calculated as weaker when the TC cloud pattern of microwave images was MW EYE or MW TEYE. For this reason, negative bias tended to be significantly larger for TCs with a maximum wind speed exceeding 90 KT. Ascertaining whether TB07H_AREA110_C10 fully covers the one-degree circle or not is effective as a judgment factor to confirm whether such cases of negative bias are particularly significant. If it does not cover the circle, there is a high chance of a significant negative bias. In the weakening stage, Shear or Curved Band in the cloud patterns of the Dvorak method often appears, and largely similar values to those of the best track are often calculated. It can therefore be concluded that analysis results with a higher level of objectivity are obtained by referring to BT_WP_Ave when TC cloud patterns of the Dvorak method are not clear for periods considered to be in the weakening stage.

From the above results, a flowchart for TC intensity estimation using the Dvorak method and microwave imagery was devised.

TC intensity estimation using the technique of Hoshino and Nakazawa (2007) can be considered to complement TC intensity analysis using the Dvorak method and enable higher levels of accuracy and objectivity.

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