An Algorithm for Tracking Eyes of Tropical Cyclones

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ABSTRACT

A tropical cyclone (TC) eye tracking (TCET) algorithm is presented in this study to objectively identify and track the eye and center of a tropical cyclone using radar reflectivity data. Twelve typhoon cases were studied for evaluating the TCET algorithm. Results show that the TCET can track TC centers for several hours. The longest tracking time is about 35 h. Eye locations estimated from different radars showed consistency with a mean distance bias of about 3.5 km and a standard deviation of about 1.5 km. The TCET analysis shows decreasing eye radius as TCs approach land, especially within 50 km of the coastline.

The TCET algorithm is computationally efficient and can be automated by using the TC center in the previous volume or the estimated center from satellite images as an initial guess. The TCET may not accurately find the TC center when a TC is weak or does not have an enclosed eyewall or when it does have highly noncircular eyes. However, the algorithm is still suitable for operational implementation and provides high spatial and temporal resolution information for TC centers and eye radii, especially for intense TCs.

1. Introduction

The eye and eyewall are signature characteristics of a mature tropical cyclone (TC), and knowing their locations is crucial for operational weather forecasts near and during TC landfalls. Several methods have been developed to identify typhoon centers using mass observations from global positioning system (GPS) dropsonde and aircraft data (Kepert 2005), and Doppler radar velocity and reflectivity fields (e.g., Lee and Marks 2000; Griffin et al. 1992). The eye region is often characterized with weak or no echoes and is surrounded by a more or less complete wall of deep convection where the extreme tangential and ascending wind velocities are located (Willoughby and Black 1996; Willoughby 1998; Blackwell 2000). According to the thermodynamic characteristics in the eye of a mature TC (Willoughby 1998), the eye can be regarded as a closed area with weak or no radar reflectivity. In past studies, Senn and Hiser (1959), Parrish et al. (1984), and Muramatsu (1986) manually tracked reflectivity echoes and reported rapid cyclonic movement around the eye. And TC centers are often subjectively identified as centroids in oval-shaped weak echo or echo-free areas (Burpee and Marks 1984; Griffin et al. 1992).

Based on Doppler velocity data, Wood and Brown (1992) and Wood (1994) developed a geometric method for determining the circulation centers of Rankine-like vortices. The method provided a direct estimation of the circulation strength, radius of maximum wind (RMW), and the center location of a TC from Doppler radar data, and could be applied in an operational environment. However, it was highly affected by the asymmetry of circulations and strong mean flows across the vortex. Marks et al. (1992) used the “simplex” algorithm (Nelder
and Mead 1965) to find the center that maximizes the tangential circulations encompassing the observed RMW at different altitudes. They found that the center was 3–6 km to the right of that determined objectively from the flight-level inertial navigation system (INS) winds. Further, Lee and Marks (2000) used the simplex concept and proposed an algorithm based on a ground-based velocity track display (GBVTD; Lee et al. 1999) wind retrieval technique to estimate vorticity centers by maximizing the GBVTD’s retrieved mean tangential wind. The GBVTD simplex can be automated such that the initial guess is assigned as the vorticity center in the previous volume or estimated from the method outlined in Wood and Brown (1992) and Wood (1994).

Even though Doppler velocity can be used to estimate TC centers and RMW, the range limitation of Doppler observations confines analyses to an area (e.g., 230 km or less for the U.S. Weather Surveillance Radar-1988 Doppler, or WSR-88D) that is usually much smaller than the reflectivity coverage (460-km range for WSR-88D). Furthermore, the strength of TCs estimated from Doppler winds will be underestimated when the ring of RMW moves near the radar site due to geometrical limitations (Wood and Brown 1992). In contrast, reflectivity data can provide center information beyond the Doppler velocity observation range and can provide stable TC tracks. For asymmetric convection, wind centers tend to be close to the more intense portion of the eyewall reflectivity maximum (Marks 1990), while reflectivity centers do not. In a well-organized TC, the dynamic (wind) center nearly always lies within the eye depicted by radar reflectivity (Foley 1995). It is suggested that a combination of reflectivity and wind centers from Doppler radar observations is necessary to determine storm positions under different eyewall structure and observation ranges (Marks 1990; Wood 1994).

The eye-tracking algorithm in Griffin et al. (1992) tried to minimize the differences in the reflectivity near the eye and eyewall between two consecutive sweeps a few minutes apart. The methodology was similar to the cross-correlation analysis used in Tuttle and Gall (1999). Since reflectivities in the eyewall tend to be intense but fairly uniform in the azimuthal direction (Tuttle and Gall 1999), the estimated TC center based on reflectivity correlations could have high uncertainties. The tropical cyclone eye tracking (TCET) algorithm proposed in this study can potentially improve the objective identification of TC eye and center locations by using an iterative procedure with multiple parameters that define the physical structure of TC eyes. The TCET algorithm is presented in section 2. Sensitivity tests and comparisons are given in section 3. Section 4 shows the TCET results and comparisons among different radars. A summary will be given in section 5.

2. Data and methodology

The strong winds and heavy rainfall associated with a TC lead to significant losses of property and human lives each year in Taiwan, even if the storm does not make landfall (Wu 2001; Wu et al. 2002). For improving the mesoscale observations of typhoons, the Central Weather Bureau (CWB) of Taiwan implemented a Doppler radar network around Taiwan Island between 1996 and 2001. The radar network covers the mountains and the surrounding ocean, providing detailed rainfall and circulation structure information on severe weather systems like thunderstorms, mei-yu fronts (Chen et al. 2005), and typhoons. These radars provide frequent information such as TC positions, tracks, and intensity changes as typhoons approach Taiwan. They also provide details of mesoscale circulations and precipitation structures in the inner cores and rainbands of typhoons as they impact Taiwan.

There are two types of Doppler radar systems operated by CWB (Table 1): the WSR-88D located at the Wu-Fen-Shan (RCWF) site and the Gematronik 1500S Doppler radars located at the Ken-Ting (RCKT), Hualien (RCHL), and Chi-Gu (RCCG) sites (Fig. 1). Because of beam blockages by topography to the east of the RCCG radar while typhoons pass over the Taiwan Strait, as well as sampling problems with storms displaying weak or disorganized eyewalls, RCCG data were not used in this study. Two scan modes were adopted for the Gematronik radar to fit the scanning strategy [volume coverage pattern 21 (VCP 21)] of the WSR-88D radar. The first mode is for surveillance, which uses low pulse repetition frequency (PRF) to obtain a long unambiguous range (460 km) in the lowest two tilts. The second mode, with nine scans, uses high PRF to obtain a large unambiguous velocity.

Different from Griffin et al. (1992), a TC center in the TCET algorithm is defined as the geometric center of the radar eye region rather than the inner edge of the eyewall. Furthermore, a circular shape is assumed in TCET for the eye of a tropical cyclone based on common observations. The iterative procedures and parameters of TCET are described as follows:

1) Make an initial guess of the typhoon center \((X^0, Y^0)\) in a Cartesian coordinate with the origin at the radar site, the eye radius \((R_0)\), and the weak echo threshold \((Z_0)\). Here, \(X^0\), \(Y^0\), \(Z_0\), and \(R_0\) can be determined subjectively with satellite or radar images or by taking the values found in the previous volume.
2) In any given \((m)\)th iteration, the estimated TC center at the lowest PPI is defined as

\[
X_m = \frac{1}{A} \int XdA, \quad Y_m = \frac{1}{A} \int YdA, \quad (1)
\]

where \((X_m, Y_m)\) is the calculated center, the superscript \(m\) indicates the iteration number, and \((X, Y)\) represents any point that has a reflectivity smaller than a prescribed reflectivity threshold \((Z_0)\) and satisfies

\[
(X - X_{m-1})^2 + (Y - Y_{m-1})^2 \leq R^2. \quad (2)
\]

Here, \(A\) is the total area encompassing all the data points that meets the above two criteria. The radius \(R\) is

![Image](image_url)

**FIG. 1.** Typhoon tracks determined by the TCET algorithm. The gray lines indicate tracks from the TCET algorithm and heavy solid lines represent the tracks determined from two or three radars at the same time. The radar sites are labeled with plus signs. Range rings of 230 km centered at each radar site are also indicated.
set to $R_0 - \Delta R$ in the first iteration, and it increases by 1 km for each new iteration until it reaches $R_0 + \Delta R$ or the convergence criteria (defined below in steps 3 and 4) is met.

3) Check if the distance between $(X_m, Y_m)$ and $(X_{m-1}, Y_{m-1})$ is larger than a prespecified convergence criterion ($a$). If yes, then the computation goes back to step 2. The iterative procedure will stop when the convergence condition is met or the iteration number is greater than a threshold ($\beta$), or when the radius of computational area, $R$, reaches its upper limit of $R_{01}$. 

4) To assure that the derived eye radius encompasses the entire eye region, an additional criterion called the enclosed rate of eye (ERE) is examined. The ERE is defined as the portion of reflectivity pixels on the boundary of the computed eye that is higher than the prespecified reflectivity threshold ($Z_0$; Table 2). If all the pixels on the boundary have weak or no echoes, then it is possible that the computed eye is smaller than the actual eye and the associated ERE is 0. As the iterative process continues, the eye radius increases and the boundary of the computed eye will eventually reach the eyewall region. Some of the pixels on the eye boundary will have reflectivities higher than the threshold, and the ERE will increase. When the ERE is equal to 1.0, it is considered that the computed eye radius has reached the outer edge of the actual eye. The iterative procedure ends if the ERE is greater than or equal to an ERE threshold, $\gamma$ (Table 2). The parameter $\gamma$ can be adjusted (i.e., set to a smaller value) to potentially extend the TCET application for TCs with unclosed eyewalls or eye regions. Sensitivity tests of parameters $\gamma$ are presented in section 3.

5) Figure 2 illustrates the iterative process of the TCET algorithm. First, an initial guess of the center was made at point A with a radius $R_0$. Point A is replaced by point B through the procedures (steps 1–3) described above. Because the distance between A and B does not meet the convergence criterion, point B is replaced with point C again. Finally, the iteration stops when the distance between C and the new center (not shown) satisfies the convergence criterion. Point C is defined as the estimated TC center and the eye radius is determined at the same time.

Default values or initial guesses of the empirical parameters and thresholds for the TCET algorithm are listed in Table 2. Two additional criteria, one on the eye radius and another on the moving speed of the TC, are applied to ensure the consistency of the eye location and eyewall size in time. If the current eye radius and speed of motion are different from the last 2-h average by more than 10 km and 10 km h$^{-1}$, respectively, the current TC position will be considered unreasonable and will be removed.

### 3. Sensitivity tests and comparisons

#### a. Sensitivity tests

The TCET algorithm was tested using 12 typhoon cases (Table 3) and the sensitivities of the algorithm to various empirical parameters were analyzed. Table 4 shows the changes of the TCET results with varying reflectivity and ERE thresholds (i.e., $Z_0$ and $\gamma$, respectively). The changes were measured with respect to the TCET results using the default reflectivity threshold (10 dBZ) and ERE (1.0). Other algorithm parameters are kept the same as those defined in Table 2.

When ERE was kept at 1.0 and $Z_0$ was reduced from 10 to 0 dBZ, the mean difference (DIFP; Table 4) in the computed TC positions was 1.2 km with a standard deviation (STDP; Table 4) of 1.2 km. The eye radius was

### Table 2. The empirical parameters and thresholds used for the TCET algorithm. Detailed discussions are found in the text.

<table>
<thead>
<tr>
<th>Parameter descriptions</th>
<th>Symbols</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak echo threshold (dBZ)</td>
<td>$Z_0$</td>
<td>10</td>
</tr>
<tr>
<td>Extend range (km)</td>
<td>$\Delta R$</td>
<td>20</td>
</tr>
<tr>
<td>Convergence criterion (km)</td>
<td>$\alpha$</td>
<td>0.1</td>
</tr>
<tr>
<td>Max No. of iterations</td>
<td>$\beta$</td>
<td>20</td>
</tr>
<tr>
<td>Enclosed rate of eye</td>
<td>$\gamma$</td>
<td>0.9</td>
</tr>
</tbody>
</table>
reduced by 1.2 km on average with a standard deviation of 2.2 km. The number of volumes with successful TC identification changed little and the relative tracking rate (TR) (to that of $Z_0 = 5$ dBZ) was 0.99. When $Z_0$ was increased from 10 to 20 dBZ, the changes in TC locations were similar to those associated with $Z_0$ changing from 10 to 0 dBZ, but the TR largely reduced by 40%. This result indicates that the high reflectivity threshold has a significant impact on TR, especially for typhoon centers that are far away from the radar. Since the altitudes of radar observations increase with increasing range and the reflectivity intensities decrease with increasing range (due to beam spreading and attenuation), radar-observed eyewalls tend to be weak or even unclosed at far ranges. These weak eyewall signatures caused TCET to not converge under the condition of ERE = 1.0 and this, in turn, resulted in fewer TC identifications. When $Z_0$ was kept at 10 dBZ and ERE was reduced from 1.0 to 0.9, TR increased by 7% and the eye radius decreased by 1.3 km on average. When ERE was decreased from 1.0 to 0.5, TR increased by 5%, but the average TC location difference increased to 2.2 km and the eye radius was reduced by 4.1 km. The sensitivities of TCET to ERE for $Z_0 = 0$ dBZ and 10 dBZ were similar, but both the differences in TC positions and eye radius (DIFER: Table 4) were larger for $Z_0 = 0$ dBZ than for $Z_0 = 10$ dBZ. The increase in TR was relatively small (Table 4). When $Z_0 = 20$ dBZ, the DIFP was similar to that for $Z_0 = 20$ dBZ, but the eye radius increased (by ~1 km) when ERE changed from 1.0 to 0.9 and decreased (by 0.6 and 2.1 km, respectively) when ERE was 0.7 and 0.5. The TR was reduced for all ERE values (Table 4) with $Z_0 = 20$ dBZ comparing to $Z_0 = 10$ dBZ, and the higher the ERE, the larger the TR reduction. These results indicate that, when the ERE value is reduced, the TCET will have larger uncertainties in the computed TC location and a relatively invariant tracking rate with $Z_0 = 0$ dBZ. But for $Z_0 = 20$ dBZ, the successful tracking rate varies significantly with changing ERE values. A high ERE value will cause a large drop in the tracking rate.

b. Limitations

Based on the sensitivity tests, it is found that ERE is a key parameter in the TCET scheme. If the unclosed part of a typhoon eye is large, the TCET could fail because the convergence criteria could not be met. This can occur with weak typhoons, with eyewalls undergoing an eyewall replacement cycle (Black and Willoughby 1992; Blackwell 2000), or when a typhoon’s eye structure is breaking apart after the landfall (Yang et al. 2008). TCET failure can also occur with typhoons far away from the radar, because the radar-observed eyewalls under this situation may have weak intensities and unclosed eyewalls, especially on the side farther away from the radar. Reducing ERE could help, but it may cause the TCET not to converge to the predefined criteria (default is 0.1 km). Relaxing the convergence criteria can increase the chance of identifying a TC center; but it could introduce large errors in the center location or even an incorrect center outside of the typhoon eye region. Since TCET assumes circular eyes, it may have problems with typhoons that have highly noncircular eyes. For instance, some typhoon eyes are elliptical. When the ellipticity is high, the TCET may not converge under a high ERE value. If the ERE value is reduced, the TCET may converge but the resultant TC center location may not be as accurate due to only part of the weak echo region being encompassed within the TCET.

The reflectivity threshold is another important parameter. Setting it too high can result in unclosed

<table>
<thead>
<tr>
<th>Typhoon</th>
<th>Date</th>
<th>Radars tracked</th>
<th>Tracking duration (h)</th>
<th>RCWF</th>
<th>RCHL</th>
<th>RKCT</th>
<th>Landfall?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herb (1996)</td>
<td>30–31 Jul</td>
<td>1</td>
<td>15.6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Nari (2001)</td>
<td>15–16 Sep</td>
<td>1</td>
<td>35.7</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Soudelor (2001)</td>
<td>17–18 Jun</td>
<td>3</td>
<td>13.0</td>
<td>2.8</td>
<td>14.0</td>
<td>—</td>
<td>No</td>
</tr>
<tr>
<td>Dujuan (2003)</td>
<td>1 Sep</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>13.3</td>
<td>—</td>
<td>No</td>
</tr>
<tr>
<td>Haitang (2005)</td>
<td>17 Jul</td>
<td>2</td>
<td>14.2</td>
<td>15.2</td>
<td>—</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Longwang (2005)</td>
<td>1 Oct</td>
<td>3</td>
<td>12.9</td>
<td>16.4</td>
<td>8.7</td>
<td>—</td>
<td>Yes</td>
</tr>
<tr>
<td>Saomai (2006)</td>
<td>9–10 Aug</td>
<td>2</td>
<td>24.1</td>
<td>7.0</td>
<td>—</td>
<td>—</td>
<td>No</td>
</tr>
<tr>
<td>Khanun (2006)</td>
<td>10–11 Sep</td>
<td>2</td>
<td>21.4</td>
<td>15.7</td>
<td>—</td>
<td>—</td>
<td>No</td>
</tr>
<tr>
<td>Shanshan (2006)</td>
<td>14–16 Sep</td>
<td>3</td>
<td>23.0</td>
<td>24.8</td>
<td>25.5</td>
<td>—</td>
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<tr>
<td>Wipha (2007)</td>
<td>17–18 Sep</td>
<td>2</td>
<td>30.3</td>
<td>19.3</td>
<td>—</td>
<td>—</td>
<td>No</td>
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<tr>
<td>Krosa (2007)</td>
<td>5–7 Oct</td>
<td>3</td>
<td>14.5</td>
<td>17.9</td>
<td>9.2</td>
<td>—</td>
<td>Yes</td>
</tr>
</tbody>
</table>
eyewalls and prevent the TCET from converging. This often occurs on the middle- and high-elevation plan position indicators (PPIs) or when typhoon eyes are far away from the radar. It can result in too small eye radii and large uncertainties in derived TC center locations if the threshold is set too low. This mostly occurs with the low-elevation PPIs and when typhoon eyes are close to the radar. Therefore, it is desirable to use relatively low $Z_0$ value (e.g., 0 dB$Z$) when typhoons are far away from the radar or land and when using the high-elevation PPIs. When typhoons are close to the radar or land, a high threshold (e.g., 20 dB$Z$) can be used. For typhoons in between, 10 dB$Z$ can be used as the default value. It would be ideal that the threshold can be dynamically adjusted based on typhoon structure and reflectivity intensities, so that the TCET can produce more accurate TC center locations for longer time periods than using a fixed threshold. In the current study, the reflectivity threshold is set to 10 dB$Z$ and ERE is set to 0.9 with the aim of minimizing the uncertainties in the TC center locations while achieving a long trackable time. Other parameters for the TCET algorithm were set to the values listed in Table 2.

c. Comparisons with the GBVTD-simplex algorithm

Doppler weather radar provides the reflectivity and radial velocity fields. Even though the radial velocity field has a much smaller coverage area than that for the reflectivity, both have been used to determine typhoon centers (see discussions in section 1). The GBVTD-simplex algorithm (Lee and Marks 2000) is a typhoon center tracking method based on radial velocity fields and is used here to assess the TCET results. Table 5 compares the typhoon center tracking results from the GBVTD simplex with those from the TCET algorithm. Since the GBVTD simplex is based on velocity data and cannot be applied to typhoons far away from the radar, only seven cases (Table 5) were used for the comparison. Each of these cases had at least 30 volume scans upon which both algorithms are applicable. Among them, Typhoon Nari (2001) had 249 applicable volume scans for both schemes because of its slow movement and provided 25 h of data applicable for the GBVTD simplex and as much as 35 h for TCET. Typhoons Aere (2004) and Wipha (2007) also provided 100+ volume scans of applicable data because they both went westward near northern Taiwan without a landfall. Table 5 shows that the mean difference between TC center locations identified from the two schemes is the smallest (2.7 km with a standard deviation of 1.4 km) for Saomai (2006). The largest difference (6.2 km with a standard deviation of 4.2 km) is for Krosa (2007). After examining the three cases (i.e., Krosa, 2007; Aere, 2004; and Herb, 1996) with relatively large differences between the two schemes, it was found that the RMW values derived from the GBVTD simplex for these cases were also large. All three typhoons had RMWs greater than 38 km, with the largest being 44.9 km for Aere. A scatterplot of all the TC center location differences (Fig. 3) shows that most of the differences are within 5 km and there is no evident bias toward any given direction. However, there are some differences greater than 20 km (Fig. 3). The differences increase with increasing RMW values, and the ratio between the two remains relatively invariant at about 12%–17% (DIFPR; Table 5), indicating a dependency of the TC center location errors on the RMW. Other factors impacting the differences include double eyewalls or the landfalling of typhoons. Lee and Marks (2000) found that 15% of the error in the center location could result in a maximum of 10% of error in the retrieved tangential wind and RMW (assuming an axisymmetric vortex). Since the TCET and

<table>
<thead>
<tr>
<th>$Z_0$ (dB$Z$)</th>
<th>Positions</th>
<th>Eye radius</th>
<th>Volumes of identification</th>
<th>Relative TR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\gamma$</td>
<td>$\Delta$E</td>
<td>$\Delta$R</td>
<td>$\Delta$F</td>
</tr>
<tr>
<td>0</td>
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<td>1.2</td>
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<td>0.9</td>
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<td>1.3</td>
<td>31.7</td>
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<tr>
<td>0.7</td>
<td>1.8</td>
<td>1.4</td>
<td>29.9</td>
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<td>0.5</td>
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<td>1.6</td>
<td>27.9</td>
<td>-5.5</td>
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<tr>
<td>10</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>34.3</td>
</tr>
<tr>
<td>0.9</td>
<td>0.3</td>
<td>0.8</td>
<td>32.9</td>
<td>-1.3</td>
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<td>0.7</td>
<td>0.9</td>
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</tr>
<tr>
<td>0.5</td>
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<td>1.4</td>
<td>29.4</td>
<td>-4.1</td>
</tr>
<tr>
<td>20</td>
<td>1.0</td>
<td>1.4</td>
<td>31.2</td>
<td>1.8</td>
</tr>
<tr>
<td>0.9</td>
<td>1.6</td>
<td>1.4</td>
<td>33.4</td>
<td>1.0</td>
</tr>
<tr>
<td>0.7</td>
<td>1.8</td>
<td>1.4</td>
<td>33.0</td>
<td>-0.6</td>
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<tr>
<td>0.5</td>
<td>2.6</td>
<td>1.5</td>
<td>31.2</td>
<td>-2.1</td>
</tr>
</tbody>
</table>
GBVTD-simplex algorithms are based on different conceptual models and observations, these differences are to be expected. Despite the differences, the TC locations determined from the TCET or GBVTD-simplex schemes are valuable in the monitoring of typhoon tracks, especially when typhoons make turns or landfalls.

Figure 4 shows a scatterplot of the eye radius derived from the TCET versus the RMWs derived from the GBVTD-simplex algorithm. The eye radius appears to be 7–12 km inside the RMWs, and the correlation coefficient between the two is 0.93. The slope (1.04) of the linear regression indicates that there is a systematic difference between the two. That is, the RMW is located about 7.5 km away from the eye boundary and the distance between the two increases with increasing eye radius. If the eye radius is 50 km, then the RMW should be about 59.5 km according to the regression. This statistical result may help with the estimation of the RMW for typhoons beyond the radial velocity data coverage.

4. Results and discussions

a. Track

The TCET algorithm was evaluated with 12 typhoon cases (Table 3). These cases included the elliptical eyewall of Typhoon Herb (1996) (Kuo et al. 1999; Wu and Kuo 1999), the concentric eyewall of Dujuan (2003) (Hong and Chang 2005), and Typhoon Nari (2001) (Yang et al. 2008). The tracking times and distances are also summarized in Table 3. Typhoon Nari (2001) had the longest tracking time of 35 h. Generally, most typhoons can be tracked for several hours (Table 3). These well-organized typhoons moved mostly along a westward or south-westward track. Some of them made landfall in Taiwan while others just passed over the sea adjacent to Taiwan (Fig. 1).

Figure 5 shows four examples of typhoons having well-organized eyewall structure as they approached Taiwan. The eye regions were a mixture of echo-free and weak reflectivity regions. The Herb eyewall (Fig. 5a) shows an elliptical shape with deep convection near the tip of the major axis as described in Kuo et al. (1999). Typhoon Nari (Fig. 5b) exhibited a relatively circular-symmetric eyewall structure with some weak-echo areas existing in the eye region. In contrast, both Typhoons Wipha (2007) and Krosa (2007) displayed asymmetric eyewall structures (Figs. 5c and 5d). The eye radius (circles at the domain center; Fig. 5) was about 35 km for Typhoon Herb and about 30 km for Typhoons Nari and Krosa. The smallest eye radius was about 15 km for Typhoon Wipha (Fig. 5c). For all cases, the eye radius was measured just inside of the

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**Table 4. Comparisons with the GBVTD-simplex algorithm.**

<table>
<thead>
<tr>
<th>Typhoon</th>
<th>Positions</th>
<th>TCET eye radius (km)</th>
<th>RMW (km)</th>
<th>Max tangential wind (m s⁻¹)</th>
<th>Volumes of the GBVTD simplex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herb (1996)</td>
<td>5.8</td>
<td>29.3</td>
<td>38.1</td>
<td>0.15</td>
<td>54.2</td>
</tr>
<tr>
<td>Nari (2001)</td>
<td>4.3</td>
<td>28.1</td>
<td>36.9</td>
<td>0.12</td>
<td>44.0</td>
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<td>32.4</td>
<td>0.12</td>
<td>39.1</td>
</tr>
<tr>
<td>Aere (2004)</td>
<td>6.0</td>
<td>37.9</td>
<td>44.9</td>
<td>0.13</td>
<td>39.7</td>
</tr>
<tr>
<td>Saomai (2006)</td>
<td>2.7</td>
<td>14.8</td>
<td>22.3</td>
<td>0.12</td>
<td>62.1</td>
</tr>
<tr>
<td>Wipha (2007)</td>
<td>4.1</td>
<td>14.8</td>
<td>24.3</td>
<td>0.17</td>
<td>54.3</td>
</tr>
<tr>
<td>Krosa (2007)</td>
<td>6.2</td>
<td>26.0</td>
<td>38.0</td>
<td>0.17</td>
<td>59.2</td>
</tr>
<tr>
<td>Total</td>
<td>4.6</td>
<td>26.0</td>
<td>34.4</td>
<td>0.13</td>
<td>47.8</td>
</tr>
</tbody>
</table>

**Fig. 3.** Differences (km) between the TC center locations derived from the TCET and GBVTD-simplex algorithms. The location differences are displayed with the TCET algorithm (“X” point) as the reference point.
edge of the eyewall. The Doppler velocities associated with the four selected typhoon examples are shown in Fig. 6. All cases showed a dipole structure (i.e., a coupled positive and negative wind speed maximum), which is typical on the radial velocity PPI images of a ground-based Doppler radar when observing atmospheric vortices such as mature tropical cyclones or tornadoes (e.g., Donaldson 1970; Jou et al. 2008). The maximum inbound and outbound velocities were about 65 and 45 m s$^{-1}$ respectively, for Typhoon Herb (Fig. 6a). A difference of $\sim$10 m s$^{-1}$ between the inbound and outbound velocities was found in Typhoons Nari and Krosa (Figs. 6b and 6d). The Doppler velocity of Typhoon Wipha exhibited a more symmetric structure with a difference of about 5 m s$^{-1}$ between the inbound and outbound velocities as the typhoon passed over the sea north of Taiwan (Fig. 6c). Under the approximation of a quasi-symmetric vortex, the asymmetry of the Doppler velocity structure may be partially contributed to by the uniform flow that is characterized by constant wind speed and direction (Brown and Wood 1991) or mean flow, which is defined as the area-averaged storm-relative wind (Marks et al. 1992). Although the Doppler radar cannot directly measure the direction and speed of the mean flow, the asymmetric signature may be helpful in estimating the mean flow and in very short-term predictions of TC motion (Brown and Wood 1991; Lee et al. 1999). However, it is inadequate to apply this approximation in highly asymmetric TCs that are nearly completely void of echoes and Doppler velocities on one side of the storm.

The GBVTD (Lee et al. 1999) method was used to retrieve the mean tangential wind and RMW with the estimated centers from the GBVTD-simplex and TCET algorithms. The differences between eye radii and RMWs based on the two different center-finding algorithms are compared. Figure 7 shows the time–radius plot of the eye radii and maximum mean tangential wind from TCET-derived centers for four typhoons. The RMWs remained almost constant until the time immediately prior to the typhoons’ landfall (Fig. 7) except for Typhoon Wipha (Fig. 7c), in which the RMW had little change during the entire time. Further, Typhoon Krosa (Fig. 7d) exhibited a double-peak structure of tangential winds, which was related to the high velocities in a spiral rainband adjacent to the eyewall (see Figs. 5d and 6d). The area of maximum wind was very wide as a result of the double peaks. The RMW decreased just before landfall, resulting in a very prominent RMW contraction at a rate of 10–25 km h$^{-1}$ (Fig. 7d). The RMW shrunk from 42 to 30 km in 30 min for Typhoon Herb (Fig. 7a), from 27 to 17 km in 1 h for Typhoon Nari (Fig. 7b), and from 35 to 20 km in 1.5 h for Typhoon Krosa (Fig. 7b). Figure 8 shows the retrieved tangential wind using GBVTD-simplex-determined TC centers. Since the maximum tangential wind is the main convergence criteria of the GBVTD simplex, the retrieved wind is stronger than those in Fig. 7. The largest difference occurred when Typhoon Wipha moved close to the radar (0304–0633 UTC; Fig. 8c), where the maximum tangential wind speed was 5–10 m s$^{-1}$ higher than those derived using the TCET centers and the RMW was 5–10 km larger (cf. Figs. 8c and 7c). Examination of the radial velocity fields (not shown) indicated that there was a lack of data in the eyewall region. The insufficient data samples caused uncertainties in the GBVTD-simplex-derived TC center location. Even though the difference was only a few kilometers, the impact on the retrieved structure was significant due to the small RMW (Fig. 8c). In contrast, the retrieved wind structure was very similar for Typhoon Nari (cf. Figs. 8b and 7b) with the speed difference being less than 3 m s$^{-1}$. Both Herb and Krosa were nonaxisymmetric typhoons, among which the former had an elliptic eye and the latter had well-organized spiral outer rainbands. The retrieved tangential winds for the two typhoons were quite similar to those based on TCET (cf. Figs. 8a,d and 7a,d), especially before the typhoons landfalls. Overall, the difference in the retrieved wind...
was less than 6 m s\(^{-1}\) and the RMW difference was within 5 km.

b. Track and eye radius comparisons between multiple radars

Since the mean distance between radars in Taiwan’s CWB radar network is about 150–200 km, some TCs (e.g., Typhoon Souderlor in 2003 and Shanshan in 2006) were captured by two or even three radars at the same time for several hours. Therefore, comparisons can be made between the TC eye locations and tracks derived from different radars. Figure 9 illustrates the differences between TC center locations derived from RCHL and from two other radars (RCWF and RCKT). The mean difference was about 3.7 km with a standard deviation

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**Fig. 5.** RCWF base reflectivities at 0.5° elevation from (a) Typhoon Herb at 1033 UTC 31 Jul 1996, (b) Typhoon Nari at 0257 UTC 16 Sep 2001, (c) Typhoon Wipha at 0500 UTC 18 Sep 2007, and (d) Typhoon Krosa 0255 UTC 6 Oct 2007. The typhoon tracks (blue lines) are overlaid with the radar reflectivity for each 240 km × 240 km domain. The blue solid circles indicate inner-eye boundaries determined by the TCET algorithm. The RCWF radar site is indicated by the black arrow.
near 1.5 km. There was a noticeable northern bias, with respect to RCHL, of TC centers derived from RCKT and a southern bias for those from RCWF. As shown in Fig. 1, most of the TC centers were located to the east-northeast of RCHL. If the attenuation of radio waves (Doviak and Zrnić 1993) and the outward tilting of the vertical eyewall are considerable, then the TC center locations computed from RCHL would show an eastward bias due to the higher radar beam altitude at the eastern eyewall. Similarly, TC centers derived from RCKT and RCWF should have a northern and a southeastern bias, respectively. The net effect would be a southern (northwestern) bias for TC centers derived from RCWF (RCKT) with respect to those from RCHL.

A comparison between the eye radii derived from RCHL and those from RCWF and RCKT is shown in Fig. 10. In spite of the observations being at different ranges from the radar, the derived eye radii showed a high correlation of 0.92. The slope of the
linear regression line is 0.99 between the eye radii computed from RCHL and from the two other radars. There was one pair with a difference larger than 10 km in Fig. 10, possibly resulting from observations at significantly different ranges from the radars. Overall, the eye radii derived using TCET from different radars are consistent. This allowed some further investigation of eye radii changes during typhoon landfalls.

c. Changing of the eye radius

Figure 11 shows the changes of TC eye radii right before TC landfalls as a function of the distance of TC centers to the land (either coastlines of Taiwan or...
The smallest eye radius was about 4–9 km for Typhoon Dujuan (2003) and the largest was about 67 km for Typhoon Aere (2003). The mean eye radius for 12 typhoons (3257 TC locations) was 25.7 km with a standard deviation of about 11.4 km. The broad distribution of eye radii shown in Fig. 11 is similar to the 15-yr climatology of the North Atlantic tropical cyclones based on ship and other surface reports, aircraft reconnaissance data, and satellite imagery (Kimball and Mulekar 2004). The shrinking of eye radii for TCs approaching the land is apparent in Fig. 11, especially for those TCs located within 200 km of the land. However, Typhoon Dujuan was an exception; the small inner eyewall radius remained constant while it passed across the southern tip of Taiwan with a trochoid-like track (Hong and Chang 2005). A similar trend for the change in TC eye radius as a function of distance to the radar is shown in Fig. 12. Owing to the eyewall’s outward slope with height, TCs at a greater distance from the radar will likely display larger eye radii than storms closer to the

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**FIG. 8.** Same as in Fig. 7 but using the centers from GBVTD simplex.
This indicates that the decreasing eye radius as a TC nears landfall may be partially due to decreasing radar-to-eye distance as the storm approaches land. Thus, the contraction of an eye’s radius with decreasing range from land occurs as result of two possible effects. One is that the TC eyewalls tilt outward with height (Jorgensen 1984; Marks et al. 1992; Liu et al. 1999). Another is the real contraction of TC eyewalls in nature. The natural contraction effect was shown in Typhoons Saomai (2006) and Wipha (2007), both of which passed over the northern sea area of Taiwan and made landfall at south coast of mainland China (Fig. 1). At distances between 250 and 350 km (close to the typhoons landfall along the coastlines of mainland China) from the RCWF radar, the eye radius did not increase with increasing range, but instead remained unchanged or even decreased (Fig. 12).

The eye contraction was further examined using a ratio of eye radii to the mean eye radius of the TCs located between 175 and 225 km from the land (Fig. 13). Due to the high sensitivity of the ratio to small eye radius, only results for eye radii larger than 10 km are shown. Figure 13 shows the ratio was smaller than 1.0 within 200 km of land and greater than 1.0 beyond 200 km. At a distance of 20 km, the ratio sharply reduces to about 0.4. In contrast, the ratio rises to about 1.6 at a range of 400 km. The decreasing speed of the eye radius change as the TCs approached the land (especially within the 50-km range) was greater than when the TCs were beyond 200 km. Assuming that the mean tilt angle of a TC eyewall is 30° (60°) from the vertical, the best-fitting third-degree polynomial curve would be the long (short) dashed line shown in Fig. 13. The contractions under these cases change slightly, but the ratio is still about 0.5 within 50 km from the land and it still decreases from 1.2 to 1.0 at a range of about 400 km. These results suggest that the eyewall contraction actually exists as TCs approach Taiwan or mainland China, and the contraction is not obvious, or there is no contraction, at ranges between 200 and 400 km.

The contraction of the eyewall (eye) is often observed in nature, especially in hurricanes with concentric eyewalls (Willoughby et al. 1982; Willoughby and Black 1996). The current study found that this contraction occurs when TCs approach land, which is similar to the eyewall contraction of Hurricane Andrew (1992) prior to its landfall at Miami, Florida (e.g., Willoughby and Black 1996). This type of contraction is possibly related to the differential friction caused by the land–sea contrast (Kepert 2006; Wong and Chan 2007) and TC–topography interactions (Powell 1987; Wu et al. 2002; Yang et al. 2008).

5. Summary

The TCET algorithm is presented to objectively identify the TC eye from radar reflectivity observations.
The TCET algorithm is also designed to automatically track the TC center and to compute the eyewall radius when the eyewall is well organized. Twelve major typhoon cases were analyzed using the TCET algorithm. Sensitivity tests show that the reflectivity threshold and enclosed rate of eye (ERE) are two key parameters for the TCET algorithm. When the ERE is set high, the TCET could fail to identify a center for TCs that have unclosed eyewalls. A high reflectivity threshold could result in an unclosed eyewall, while a too low threshold could result in a small eye region and large uncertainties in the computed center location. The results from the TCET algorithm showed that the longest tracking time was about 35 h. Further analyses based on the TCET output showed a decrease in eye size as TCs approach land, especially when the TC center was within 50 km of land.

The TCET algorithm was compared with the GBVTD-simplex algorithm. The mean difference between the TC center locations from the two schemes was 4.6 km and the standard deviation was 3.5 km. Large differences appeared to be associated with large RMWs, but the relative error (TC center difference/RMW) was nearly constant (12%–17%). The maximum tangential winds retrieved from GBVTD using the two types of TC center locations (one from TCET and the other from the GBVTD simplex) are similar, with only about a 10% difference on average. However, when there is a lack of radial velocity observations in the eye region, the GBVTD-simplex algorithm has large uncertainties, resulting in a large difference between the retrieved tangential winds based on TCET and GBVTD-simplex derived TC centers. And this impact is especially high on typhoons with small RMWs. Analyses also show that even with the same TCET scheme, TC center locations computed from different radars can be a few kilometers apart due to the different distances from the radars to the TC and physical factors such as radio signal attenuation and the tilting of eyewalls.

Generally, the TCET can be applied to determine TC centers for a wide variety of eye and eyewall shapes in radar reflectivity fields (Lewis and Hawkins 1982; Herb 1996; Nari 2001; Soudelor 2003; Dujuan 2003; Aere 2004; Haitang 2005; Longwang 2005; Khanun 2006; Saomai 2006; Shanshan 2006; Wilma 2007; Krosa 2007).
Muramatsu 1986; Kuo et al. 1999). But the TCET could fail when the convection band in the eyewall region is too narrow and the ellipticity of the eye region is too high. Therefore, the assumption of a circular eye needs to be modified and expanded to enhance the applications of TCET in future work. The TCET may not accurately find the TC center when a TC is weak or does not have an enclosed eyewall. And the TCET procedure may not work effectively when the storm is undergoing an eyewall replacement cycle or when the outer eyewall is stronger than the inner eyewall, thereby producing gaps in the track. Nevertheless, since the most damaging TCs are usually intense (Pielke and Landsea 1998) and have well-organized eyewall structure, the TCET can be a useful operational tool under these circumstances.

The TCET is automatically operated on reflectivity data alone and is computationally efficient. Each TCET run takes less than 10 s on a Hewlett-Packard (HP) ProLiant DL585G3 computer. The initial guess of a TC center can be obtained from the center location in the previous volume or estimated from satellite images. Implementation of the TCET algorithm in real time is simple and straightforward. The algorithm has been successfully applied by the Central Weather Bureau of Taiwan in numerous typhoon cases since 2003. The TCET algorithm has also been applied to brightness temperature fields from satellite infrared images. The TC center information could be helpful for the dealiasing of Doppler velocities in tropical cyclones. Despite the success of some existing dealiasing algorithms for Doppler velocity (e.g., Eilts and Smith 1990; Zhang and Wang 2006), they still face challenges in some extreme conditions such as isolated storms or in complex terrain with no ancillary wind data. The TC center information provided by the TCET, combined with the conceptual model of a Rankine-like vortex, and the estimated wind maximum and radial profile of tangential winds, provide very useful ancillary data for an accurate velocity dealiasing near TC inner cores. Follow-up research will focus on techniques that integrate Doppler velocities and reflectivities to provide more accurate information.

![Fig. 12. Eye radii of TCs as a function of the distance of the TC centers to radars for selected typhoons.](image)
about center locations, tracks, eyewall contractions, intensities, and intensity changes for landfalling TCs.

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