Objective Tropical Cyclone Center Tracking Using Single-Doppler Radar

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ABSTRACT

This study presents an extension of the ground-based velocity track display (GBVTD)-simplex tropical cyclone (TC) circulation center–finding algorithm to further improve the accuracy and consistency of TC center estimates from single-Doppler radar data. The improved center-finding method determines a TC track that ensures spatial and temporal continuities of four primary characteristics: the radius of maximum wind, the maximum axisymmetric tangential wind, and the latitude and longitude of the TC circulation center. A statistical analysis improves the consistency of the TC centers over time and makes it possible to automate the GBVTD-simplex algorithm for tracking of landfalling TCs. The characteristics and performance of this objective statistical center-finding method are evaluated using datasets from Hurricane Danny (1997) and Bret (1999) over 5-h periods during which both storms were simultaneously observed by two coastal Weather Surveillance Radar-1988 Doppler (WSR-88D) units. Independent single-Doppler and dual-Doppler centers are determined and used to assess the absolute accuracy of the algorithm. Reductions of 50% and 10% in the average distance between independent center estimates are found for Danny and Bret, respectively, over the original GBVTD-simplex method. The average center uncertainties are estimated to be less than 2 km, yielding estimated errors of less than 5% in the retrieved radius of maximum wind and wavenumber-0 axisymmetric tangential wind, and ~30% error in the wavenumber-1 asymmetric tangential wind. The objective statistical center-finding method can be run on a time scale comparable to that of a WSR-88D volume scan, thus making it a viable tool for both research and operational use.

1. Introduction

A two-dimensional (2D), horizontal, tropical cyclone (TC) circulation represented in a Cartesian coordinate system is often transformed to a cylindrical coordinate system with an origin at the TC's center and subsequently decomposed into azimuthal wavenumber harmonics (e.g., Marks et al. 1992; Willoughby 1992; Reasor et al. 2000, 2009). The wavenumber-0 component then represents the azimuthal mean (axisymmetric) structure, with higher wavenumbers representing azimuthal asymmetries. The importance of an accurate TC center during the aforementioned procedure was emphasized in Willoughby (1992), where an artificial asymmetric wavenumber-1 structure would be generated from transforming a 2D axisymmetric TC wind field from a Cartesian to a cylindrical coordinates if an incorrect TC center were specified. Identifying an accurate TC center is extremely important in single-Doppler TC wind retrieval algorithms, such as the velocity track display (VTD) family of algorithms (Lee et al. 1994, 1999; Roux and Marks 1996; Jou et al. 2008), because each possible center provides a unique wind solution for a given set of Doppler velocity observations.

Marks et al. (1992) suggested the use of the "circulation center" that produced the maximum circulation enclosed by the radius of maximum wind (RMW) using a simplex method (Nelder and Mead 1965) for dual-Doppler radar

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studies of TCs. Lee and Marks (2000, hereinafter LM00) followed Marks et al. (1992) and proposed a ground-based VTD simplex algorithm (GBVTD-simplex) to identify a TC circulation center (referred to as ''center'' for brevity) that maximizes the axisymmetric tangential wind retrieved from the GBVTD algorithm. The radius where this maximum axisymmetric wind occurs is the RMW. LM00 showed that errors in the GBVTD retrieved wavenumber-1 asymmetry could be greater than 20% if the center was displaced by more than 1 km in a storm with a 20-km RMW, or about 5% of the RMW. Minimizing the error in TC center estimates is therefore critical for accurate TC wind reconstruction and analysis using single-Doppler data.

On tests with analytic TCs the GBVTD-simplex algorithm was shown to be accurate to 0.34 km even in the presence of random (5 m s^{-1}) noise. The error in this case arose from the data-smoothing effect by interpolation and coordinate transformation of the simulated Doppler radar data. LM00's analysis of Typhoon Alex (1987) suggested that the center uncertainty was between 1 and 2 km for a real TC. This uncertainty estimate was based on the standard deviation of mean center locations calculated from the consensus of all available simplex centers from different initial guesses. Although Alex's centers were plausible, LM00 was not able to assess the accuracy of the GBVTD-simplex-derived centers without independent measurements from a second Doppler radar or in situ measurement from reconnaissance aircraft.

Murillo et al. (2011, hereinafter M11) assessed the accuracy of the GBVTD-simplex algorithm by comparing independent centers from two different Weather Surveillance Radar-1988 Doppler (WSR-88D) units with nearly perpendicular viewing angles for Hurricane Danny (1997). Although all these centers satisfied the GBVTD-simplex criteria (LM00), they sometimes possessed large fluctuations of TC characteristics (e.g., RMW and maximum tangential wind) on the same storm from one volume to the next (~6 min) that are not physically plausible. M11 were able to further reduce the mean errors of the centers to below 2 km by subjectively reselecting an optimal set of centers by preserving temporal and spatial continuity of the RMW, maximum axisymmetric tangential wind, and storm track. However, this manual process was very time consuming and was not ideal for analyzing large research datasets or for real-time operation.

This paper presents an ''objective statistical center-finding method'' that builds upon the results of LM00 and M11 and produces a temporally, spatially, and meteorologically consistent TC track from a superset of center solutions derived from the GBVTD-simplex center-finding algorithm. The objective statistical center-finding method presented here improves upon both the ''original GBVTD-simplex'' algorithm presented in LM00, which was objective but did not fully utilize statistical information in the center estimate, and the ''subjective statistical'' method presented in M11, which utilized additional statistical information but was not fully objective. The objective statistical method can therefore provide an objective set of center estimates from many hours of single-Doppler radar data with limited user input to be used for subsequent wind field retrieval, high-resolution track analysis, or other research or operational purposes.

To test and validate the method, this paper analyzes two TCs, Hurricanes Danny (1997) and Bret (1999), which were both observed simultaneously from different angles by two WSR-88D units. These two datasets allow statistical examination of the differences between independently derived centers, axisymmetric tangential wind, and RMW, and can therefore provide uncertainty estimates (i.e., confidence measures) of the derived TC characteristics.

Section 2 reviews the GBVTD-simplex algorithm and some challenges in circulation center identification. Section 3 details the algorithm of the objective statistical center-finding method. Section 4 presents the results of sensitivity tests regarding the algorithm parameters. Section 5 presents results of two case studies where the method was applied to Hurricane Danny and Hurricane Bret. The estimated uncertainty of the centers determined by the method is presented in section 6, and a summary is presented in section 7.

2. Review of the GBVTD-simplex algorithm and its ambiguities

The logical approach of using the GBVTD-simplex algorithm to find the *optimal center* from the full-resolution Doppler radar data (WSR-88D level II) can be summarized as follows (LM00). The analysis is performed at different altitudes on constant altitude plan position indicators (CAPPIs). Specific terms used to describe the algorithms in this paper are italicized and defined in each step.

1) Subjectively estimate a *TC center rough estimate* and its corresponding RMW (referred to as *rough estimate RMW*) from the single-Doppler velocity dipole signature (e.g., Wood and Brown 1992; Wood 1994; Harasti et al. 2004) or reflectivity (e.g., Griffin et al. 1992; Chang et al. 2009). The TC center rough estimate is a single crude estimate of the center used to initialize the algorithm.
2) Prescribe a set of TC *center guesses* surrounding the TC center rough estimate to initiate the GBVTD-simplex

center-finding algorithm runs (step 3). The set of center guesses may consist of either 9 (3×3), 16 (4×4), or 25 (5×5) grid points.[1]

3) Perform GBVTD-simplex searches at a range of radii (centered on the rough estimate RMW) from the above set of initial TC center guesses yielding a set of *simplex centers.* A simplex center is a single solution to a GBVTD-simplex search initiated from a center guess for a given radius. There are therefore 9–25 simplex centers for each radius and altitude for a given radar volume.
4) Compute the mean and standard deviation of the simplex center*s* corresponding to each radius in the calculated range (referred to as *mean center* and *mean center standard deviation*).
5) Remove outliers from the simplex centers farther than one mean center standard deviation away from the mean center corresponding to each radius. This forms a set of *converging centers* that is usually less than the original 9–25 simplex centers.
6) Compute the mean and standard deviation of all converging centers corresponding to each radius to yield a set of *preliminary centers* at each radius. The preliminary center corresponding to the radius with the highest axisymmetric tangential wind (e.g., the RMW) at each altitude is then selected for use in subsequent wind analysis with the GBVTD technique. The accompanying standard deviation is used as a proxy of the TC center uncertainty.

In the original GBVTD-simplex method, the selection of an optimal TC center from the set of preliminary centers is the final step of the algorithm. The objective statistical method presented herein performs additional steps beyond the original algorithm to improve the center estimates. The preliminary centers and their corresponding TC characteristics obtained from the original GBVTD-simplex method are used for further processing to determine the *final centers* in the proposed objective statistical method. The final centers are the end result of the objective statistical method presented herein.

The GBVTD-simplex algorithm was tested in LM00 on a Rankine combined vortex for which there is only one ‘‘true center’’ that satisfies the above conditions, and all GBVTD-simplex runs starting from the center guesses converge to the true center with uncertainties of less than one-half of the spatial resolution used in the radial direction. In real TCs, different initial center guesses may converge to different locations because of TC structures deviating from Rankine combined vortices, missing data, or the existence of multiple ‘‘local’’ circulation centers associated with mesovortices. Multiple center guesses are used to identify the ‘‘system scale’’ circulation center through a consensus of the converging centers starting from different locations. LM00 noted that the uncertainties of the GBVTD-simplex algorithm increased when applied to Typhoon Alex according to the standard deviation of the converging centers. M11 conducted a thorough examination of the GBVTD-simplex results over a 6-h period (~100 volumes each from KMOB and KLIX) in Hurricane Danny (1997) and experienced many challenges in using the GBVTD-simplex algorithm. The uncertainties and challenges described by LM00 and M11 provide part of the motivation for the current study.

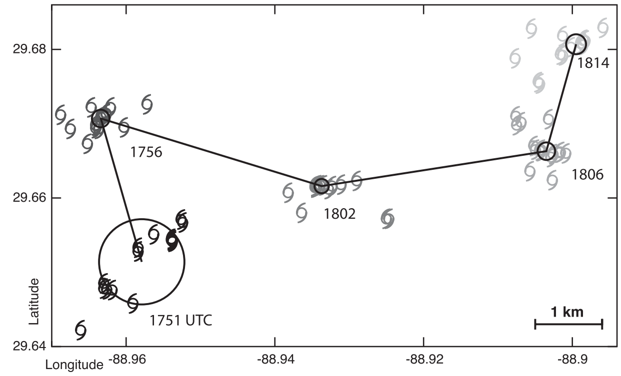

FIG. 1. Composite of simplex center and preliminary center locations for Hurricane Danny at 1751, 1756, 1802, 1808, and 1814 UTC from the KLIX radar 2-km altitude (black to light gray). Hurricane symbols indicate individual simplex centers for RMW at each time. Center of solid circles show the preliminary centers calculated at each time, with the standard deviation of the mean indicated by size of circle (0.663, 0.125, 0.131, 0.131, and 0.090 km, respectively).

Figure 1 shows a detailed look at the GBVTD-simplex-derived preliminary centers and their standard deviation (black circle in each box), along with individual simplex centers (TC symbols) in Hurricane Danny for five consecutive radar volumes. Figure 1 suggests that the preliminary center might not always be representative when multiple clusters of simplex centers are present. For example, at 1751 UTC, GBVTD-simplex found multiple clusters of simplex centers that might identify several ‘‘local’’ circulation centers. It may therefore be more appropriate to choose the final center from one of the simplex centers in one major cluster with similar TC characteristics, rather than averaging simplex center*s* from multiple clusters with different TC characteristics.

[1] It is expected that these center guesses surround the true TC center to minimize the chances of missing the absolute extremum (LM00). Also see discussions in section 4.

Figure 2 shows several idealized radial profiles of tangential wind that are likely responsible for the scattering and clustering of simplex centers in Fig. 1. In Fig. 2a, the flat gradient near the peak axisymmetric tangential wind may lead to an ambiguous RMW estimate. Relatively flat radial gradients of tangential wind like this may be found in some TCs, such as Hurricane Danny analyzed in this study. Differences in the GBVTD-derived axisymmetric tangential wind at successive radii can be small and within the uncertainties of the observations and the intrinsic assumptions of the GBVTD algorithm. Therefore the radius with the "absolute" maximum axisymmetric tangential wind may not be the "true" RMW owing to these uncertainties.

Figure 2b illustrates a radial profile of axisymmetric tangential wind with two distinct peaks where the accompanying Doppler velocity pattern possesses two dipoles, each with approaching and receding Doppler velocity extrema. This may occur in a TC with concentric eyewalls, as a TC undergoes an eyewall replacement cycle, or as it interacts with terrain upon landfall. If the magnitudes of the two peaks are similar, oscillation of the RMW and center location are possible when the maximum axisymmetric tangential wind is the only criterion considered in the GBVTD-simplex algorithm. Sometimes the GBVTD-simplex algorithm may pair the inner tangential wind maximum's approaching Doppler velocity extremum with outer tangential wind maximum's receding Doppler velocity extremum, or vice versa, yielding an erroneous center. In some situations, the double eyewall may not be concentric, with the inner eyewall making trochoidal motions as in Typhoon Dujuan (2003) (Hong and Chang 2005). In this situation, GBVTD-simplex will identify one center for each eyewall with a different RMW. However, reconstructing the wind fields for the entire vortex using the GBVTD technique will be difficult in this situation.

In addition to ambiguities in storm structures, limited Doppler range and inhomogeneous precipitation distributions often cover only a portion of a TC resulting in significant data gaps. Experience with the GBVTD-simplex algorithm has indicated that missing data beyond the Doppler range can cause poor least squares fits and unreasonably high tangential wind values increasing with radius as the missing data sector increases (Fig. 2c). GBVTD limits higher-order wavenumber fits in the presence of data gaps to avoid Gibbs oscillations, but unreasonably high tangential wind values are sometimes evident when the eyewall is near the edge of Doppler range. Unreasonably high tangential winds are also possible when there is a lack of scatterers in the eye, between rainbands, or highly asymmetric convection. Other potential radar quality issues include velocity

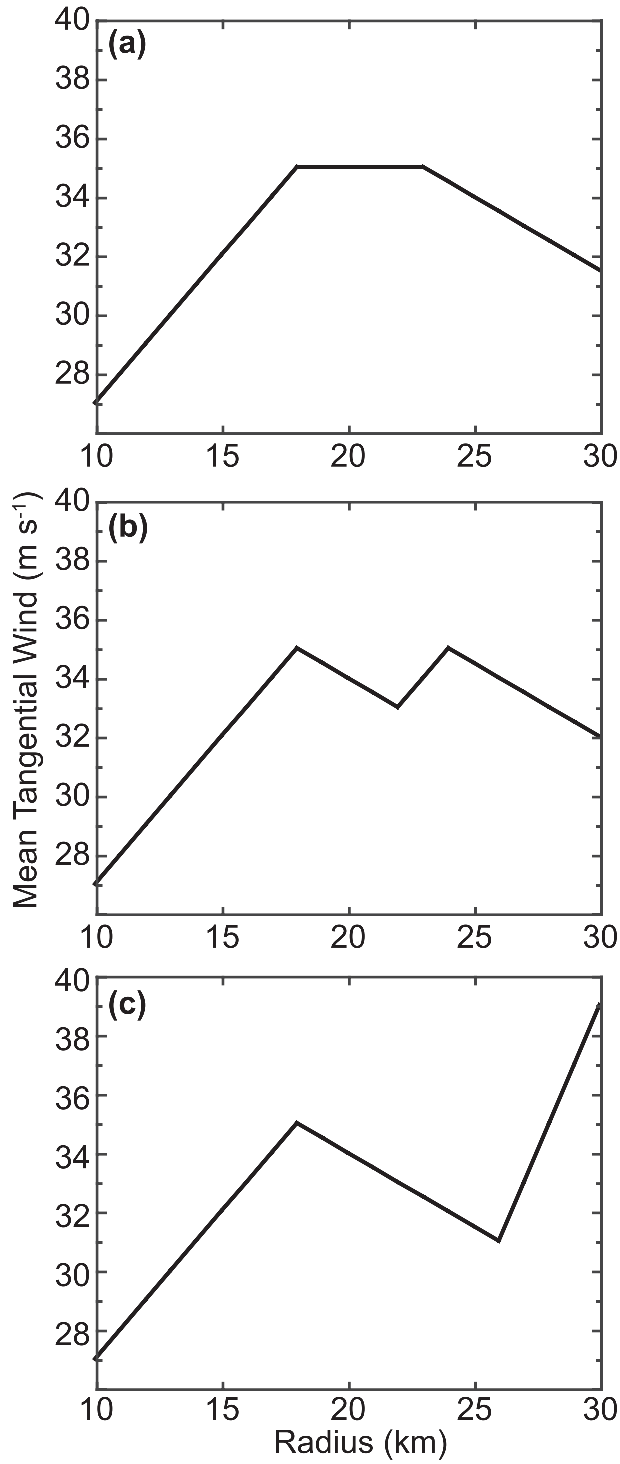

FIG. 2. Idealized radial profiles of axisymmetric tangential wind that are difficult for automatic circulation center finding. (a) Ambiguous RMW due to flat tangential wind profile, (b) ambiguous RMW due to double eyewall, and (c) false maximum due to lack of data.

aliasing, second trip echoes, ground and sea clutter returns, and uneven data resolution due to beam spreading at longer ranges. Radar data can be corrected or removed through interactive editing or automated techniques (Ellis et al. 2003; Kessinger et al. 2003; Oye et al. 1995), but some artifacts can still remain after these quality control procedures and create unrealistic radial profiles of tangential wind by the GBVTD algorithm.

As demonstrated in M11, subjective examination of spatial and temporal consistency of the radar data and GBVTD-simplex results can often reveal many of these aforementioned situations, resulting in a better determination of the center and RMW. Because of the high temporal resolution of the WSR-88D data (5–6 min per volume scan), Doppler coverage of landfalling TCs is typically available from several hours from a single radar to several days from multiple radars. As a result, the subjective examination used in M11 becomes very time consuming with a dataset of even only a few hours, and is not suitable for operational purposes. Based on the approaches taken in M11, a more objective and automated procedure is proposed in the next section to mitigate center estimation errors and provide a reliable track with physically consistent TC structures.

3. The objective statistical center-finding method

This objective statistical center-finding method improves upon the original GBVTD-simplex algorithm (LM00) and the subjective statistical center-finding method (M11) in three primary ways. First, by using an automated approach it is significantly faster and easier than the previously used subjective examination approach, and can also provide objective uncertainty estimates about the three primary derived meteorological characteristics of a TC (the center location, the maximum axisymmetric tangential wind, and the RMW). Second, by utilizing spatial and temporal continuity of three primary derived meteorological characteristics and statistical information from the scattering of the simplex centers, it can improve many of the difficulties in center estimation inherent in the original GBVTD-simplex algorithm and provide a physically consistent set of TC centers. Last, the final center is selected from one of the simplex centers, rather than from a preliminary center that may be an average of multiple clusters (cf. Fig. 1). This method can therefore provide more accurate and stable estimates of the axisymmetric tangential wind, RMW, and circulation center from a single-Doppler radar over a significant period of time. All steps in this method are performed independently at each altitude to account for vertical variation of TC centers. A flowchart of the method is shown in Fig. 3 outlining the overall steps that will be presented here in detail.

a. Determine preliminary track using normalized radial mean (NORM) score

The first step is to examine the radial profile of axisymmetric tangential wind derived from the preliminary centers for each radar volume and height. Inflection points that represent local wind maxima are located in the radial profile to identify preliminary estimates of the RMW and center location. An example of the radial profile of tangential winds is shown in the left-hand column of Table 1, taken from representative GBVTD-simplex results from Hurricane Danny at 1-km altitude. Two inflection points are evident in the radial profile of tangential wind at 16 and 23 km. Radii more than 1 km away from the inflection points are then removed from initial consideration for the RMW. The initial thresholding aims to retain data near relative wind peaks, but helps remove obviously low winds or false maximums at large radii like that seen in Fig. 2c. In the example, six radii are retained and are "qualified" for further consideration (column 2 in Table 1). However, radii that are disqualified at this point are reconsidered in the final step of the method (section 3c), ensuring that potentially good center estimates are not necessarily overlooked.

After the initial thresholding step, the maximum axisymmetric tangential wind, the number of converging centers, and standard deviation of the converging centers at each radius are normalized. The best value for each parameter among all the qualified radii is assigned a score of one, and corresponding parameters from the other remaining radii are normalized relative to the optimum value. The tangential wind and number of converging centers are normalized on log scales, while the standard deviation of the preliminary center location is normalized on a linear scale. The log scale is necessary to more effectively differentiate the weights of TC characteristics whose spreads are in narrow ranges. The axisymmetric tangential wind often varies by only 1–2 m s^{-1} in the vicinity of the RMW, and in the example the normalized value is calculated by an exponential function with an *e*-folding of 1 m s^{-1}. The normalized converging centers values are calculated by 1 + ln[(No. converging centers)/(No. center guesses)], which heavily penalizes very low convergence but is approximately linear for 12 or more converging centers (there are 16 center guesses in this example). Standard deviations of the center locations vary from hundreds of meters to several kilometers and can be adequately sorted with a linear scale.

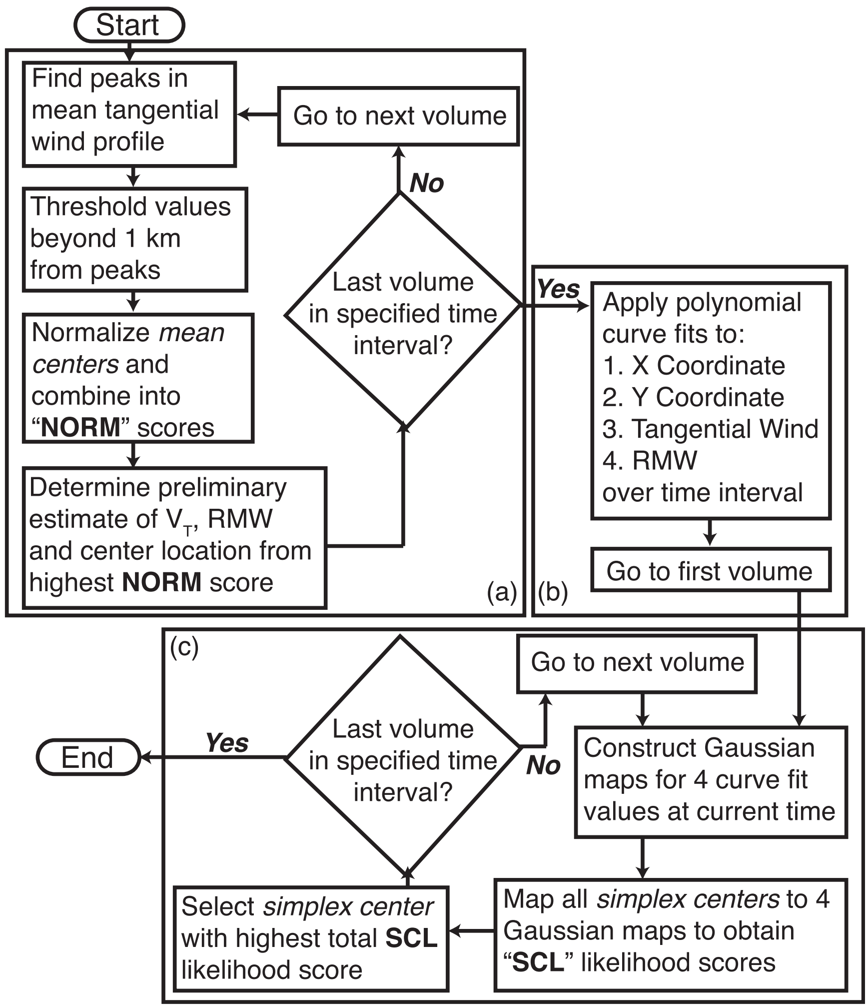

FIG. 3. Objective statistical center-finding method flowchart. Large boxes group steps described in sections 3a, 3b, and 3c, respectively.

Ideally the highest mean tangential wind, highest number of converging centers, and lowest standard deviation will all be collocated at a particular radius (i.e., the RMW), but in practice this is not always the case. In the original GBVTD-simplex algorithm, only the highest axisymmetric tangential wind was used as the criterion for selecting the RMW. In the objective statistical method, the preliminary estimate of the RMW is determined by a weighted combination of all three of these criteria. The total NORM score is obtained by combining the three weighted normalized values together. The optimal weights for the three criteria were determined empirically (see section 4). The radius with the highest NORM score is used as a preliminary estimate for the RMW for that radar volume time and height. The preliminary center and axisymmetric tangential wind associated with that radius are then used in the next step of the algorithm. In the example shown in Table 1, the maximum tangential wind and lowest standard deviation of converging centers are collocated at the 16-km radius, giving this radius the highest NORM score (right-hand column). A secondary wind maximum is found at 23-km radius, but the weaker tangential wind and higher standard deviation yield a much lower NORM score.

The NORM score is computed independently for multiple radar volumes in the time period of interest, such that preliminary estimates of the TC center and structure are obtained for each radar volume and height. The original GBVTD-simplex algorithm is similar to the objective statistical method as described up to this point, with the exception of a single criterion used to determine the center estimate (e.g., the maximum axisymmetric tangential wind) as opposed to the multiple criteria used in the NORM score. In the objective statistical method, all the TC characteristics obtained from the GBVTD-simplex algorithm and the associated NORM

TABLE 1. Mean tangential wind (VT), standard deviation of mean center location, number of converging centers out of 16, and normalized scores for each parameter. Dashes represent thresholded values, boldface indicates values retained after thresholding, and italics indicate the preliminary center chosen for this radar volume. Results are shown for Hurricane Danny at 1802 UTC from KLIX radar at 1-km height.

Radius (km)	Mean VT (m s^{-1})	Normalized VT	Std dev (km)	Normalized std dev	No. of converging centers	Normalized converging centers	Weighted NORM score
10	23.6		0.66		10		
11	22.3		4.90		11		
12	27.1		1.94		11		
13	29.4		1.36		12		
14	29.8		0.86		10		
15	**32.3**	**0.27**	**0.44**	**0.29**	**13**	**0.79**	**0.39**
16	***33.6***	***1.00***	***0.13***	***1.00***	***12***	***0.71***	***0.94***
17	**33.2**	**0.64**	**0.74**	**0.17**	**12**	**0.71**	**0.37**
18	31.7		0.61		13		
19	31.6		0.28		13		
20	31.4		0.36		13		
21	31.1		0.35		10		
22	**30.9**	**0.06**	**2.79**	**0.05**	**9**	**0.43**	**0.16**
23	**31.2**	**0.09**	**1.30**	**0.10**	**13**	**0.79**	**0.30**
24	**31.0**	**0.07**	**1.36**	**0.09**	**12**	**0.71**	**0.27**
25	29.6		1.00		11		
26	29.2		3.19		8		
27	28.5		0.73		12		
28	28.0		0.84		14		
29	27.6		1.16		13		
30	27.2		2.53		12		

scores form the database for further statistical analysis to determine the optimal final centers and their accompanying properties.

b. Apply least squares curve fits over time

The spatial and temporal continuity of the solutions is examined next using the results obtained in the previous subsection. Least squares polynomial curve fits are applied to the preliminary RMW, axisymmetric tangential wind, and center locations over the period of available data. Latitudinal (Y) and longitudinal (X) positions of the preliminary centers are fitted independently so that nonlinear motion can be preserved. A statistical F test is performed to determine the minimum degree of polynomial that fits the data well.[2] The four resulting time series then provide estimates of the TC track and structural evolution over time. Since TC evolution typically occurs on longer time scales than the radar scan, the RMW of an ambiguous radar volume can be determined more confidently (i.e., constrained) when compared to other volumes of nearby times. The analysis of the TC evolution is critical to resolving accurate centers when the radial gradient of tangential wind is weak.

Examples of the preliminary center time series for Hurricane Danny are shown in Fig. 4. Outlier centers contribute little weight to the least squares fourth-degree polynomial curve fits. The variance of the curve fit is retained in addition to the time series itself, indicating the quality of the fit to the consensus solutions. The variance of the fit is similar for both curves (1.2 and 1.3 km for X and Y, respectively). Figure 4 suggests there may be higher frequency oscillations in the position that are not captured by the fourth-degree polynomial fit. However, the low-order polynomial does a reasonable job of capturing the primary storm motion. At this stage, the overall trend rather than the volume by volume fluctuation is the focus.

c. Select final center using SCL score

The final step in the method is to select a final center for each height and radar volume using the four time series polynomial curves constructed in the previous step. The standard deviation of the overall curve fit and value of each time series polynomial curve at the radar scan time are used to construct a normalized Gaussian function as a ‘‘likelihood score’’ illustrated in Fig. 5. The characteristics of all available simplex centers from the

[2] The F test is used to determine whether the standard deviations of two polynomial curve fits of different degree are statistically equal. If the higher-order polynomial does not exceed the critical value of the F distribution at the 95% significance level, the lower-order polynomial is used.

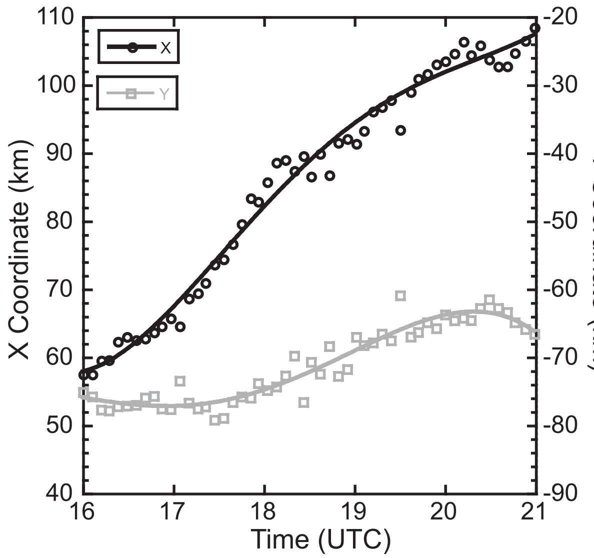

FIG. 4. Polynomial curve fits of preliminary center coordinates over 5-h period in Hurricane Danny. Black circles indicate mean X coordinates and gray squares indicate mean Y coordinates at each time from KLIX radar at 2-km altitude. Solid lines show fourth-degree polynomial fits.

radar volume are mapped onto four corresponding Gaussian functions, with likelihood scores from 0 to 1 obtained for each characteristic. In this example, the polynomial curve fit values for the center X coordinate 82.1 km east of the radar and the Y coordinate 75.6 south of the radar are considered the most likely values for the TC center and are assigned a likelihood of one. The likelihood falls off exponentially according to the standard deviation of the polynomial curve fit. The standard deviation of the X curve fit is 2.7 km, resulting in a wider Gaussian width than the Y coordinate map that has a standard deviation of 2.0 km.

The four likelihood scores for X, Y, RMW, and axisymmetric tangential wind at each radar volume are then weighted and combined in a similar manner to the NORM score. The optimal weights for the four characteristics were determined empirically (see section 4). A simplex center likelihood (SCL) score is obtained for each simplex center from the weighted combination of the four likelihood scores. The simplex center with the highest SCL score at each time and height is then selected as the optimal circulation center for that radar volume at each height. A new set of Gaussian functions and SCL scores are created for each succeeding radar volume based on the curve fit values at each successive time.

It is important to note the distinction between the NORM and SCL scores. In the first step of the method, the preliminary centers are ranked by the NORM score to

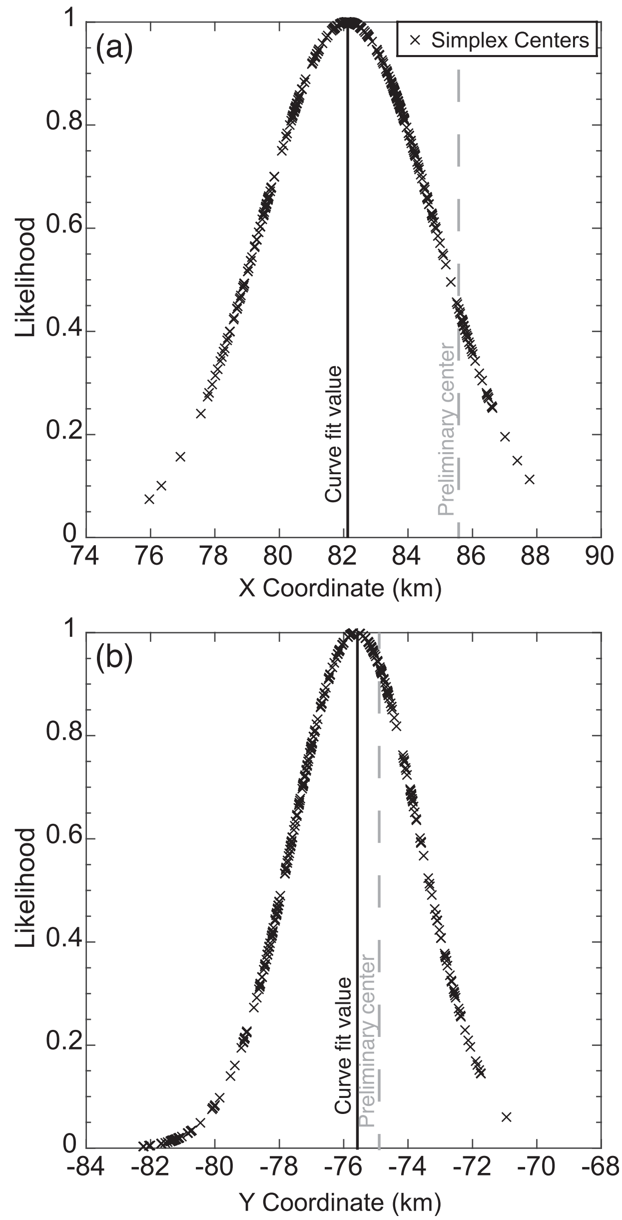

FIG. 5. Gaussian membership functions for (a) X coordinate and (b) Y coordinate. Predicted value of curve is assigned a likelihood of 1 (82.1 and −75.6 km, respectively; solid black line) and width of spectrum is determined by standard deviation of curve fit (2.7 and 2.0 km). All simplex centers for that time and height are mapped to the functions with times signs. The gray dashed lines indicate the preliminary centers used in the curve fits.

establish a preliminary TC track and meteorological evolution. During the last step of the method, the simplex centers are ranked by the SCL score through Gaussian likelihood functions derived from the preliminary track. A *preliminary* estimate of the RMW, tangential wind, and center location is obtained from the preliminary center with the highest NORM score. The *final* RMW, tangential wind, and center location are obtained from the simplex center with the highest SCL score. Since the thresholding used to determine the preliminary track is somewhat crude, the complete set of simplex centers is ranked to avoid missing potentially good centers. The *final track* is therefore composed of the simplex centers from each volume that best satisfy the temporal continuity of position, RMW, and maximum axisymmetric tangential wind.

4. Sensitivity tests

The GBVTD-simplex algorithm can be run given a few input parameters: 1) a list of initial center guesses used to initialize simplex searches, 2) a range of possible RMW estimates, and 3) the maximum azimuthal wavenumber allowed in the GBVTD analysis of the Doppler velocities. LM00 showed that the GBVTD-simplex algorithm was not sensitive to the location of TC center rough estimate as long as it was not significantly displaced from the actual circulation center. A sensitivity test performed for the current study examined the number of center guesses used to initialize the simplex searches. A comparison of 9, 16, and 25 points suggested that sufficient consensus of simplex centers could be reached with 16 center guesses. The difference in CPU time from 9 to 25 points was not significant, and the GBVTD-simplex algorithm can be completed in less than five minutes on a modern workstation, or less than that of a typical WSR-88D volume scan. To execute the algorithm through an adequate range of reasonable RMW values is not computationally demanding and was not considered a sensitive parameter. M11 tested the sensitivity to the maximum azimuthal wavenumber and found that including only wavenumbers 0 and 1 gave the best results for Hurricane Danny center estimates. These results were confirmed in this study with Hurricane Bret (not shown). In this study, sensitivity tests for the objective statistical method were performed to determine the optimal weights in the NORM and SCL scores, and the time interval for polynomial curve fitting. Optimal weights were determined by minimizing the mean distance between circulation center estimates of Hurricanes Danny and Bret from two different radars. The mean distance was calculated by linearly interpolating the center locations to 1-min intervals to account for different scan times of the two radars, calculating the distance at equivalent times, and averaging the results over the available 5-h dataset.

Different combinations of relative weights for the NORM score were compared with a control run where the statistics were weighted equally. This test indicated that the standard deviation of the preliminary centers (i.e., scatter among all converging centers of a volume) was the most valuable statistic for the NORM score (section 3a), with a suggested weight of 3 as compared with 1 for the other parameters (axisymmetric tangential wind and number of converging centers). This indicates that strong agreement among all converging centers, which was used as a confidence index in the original GBVTD-simplex method, is important when selecting the optimal preliminary center. A test to determine the optimal combination of SCL parameters was conducted by varying the relative weights of position, axisymmetric tangential wind, and RMW likelihood scores in a similar manner. The results suggested that a weight of 2 for the position and RMW as compared with a weight of 1 for the axisymmetric tangential wind for the SCL score produced optimal results.

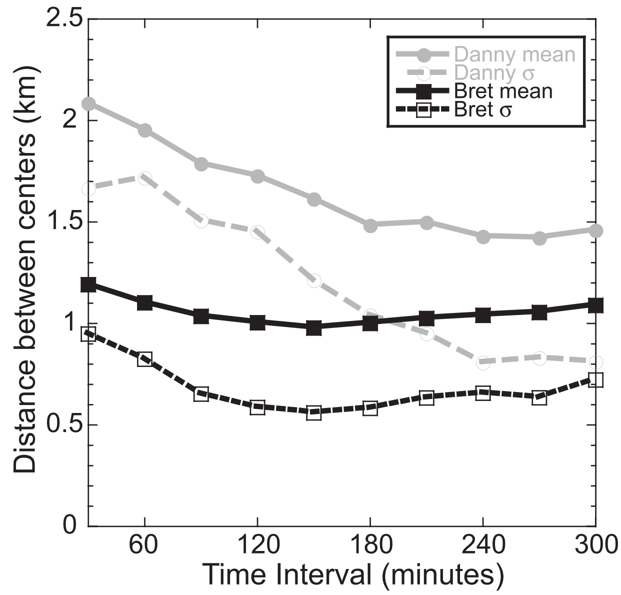

FIG. 6. Sensitivity of the objective statistical center-finding method to the time interval used for curve fitting. The means (solid lines) and standard deviations (dashed lines) of the distance between independently determined single-Doppler center estimates over each time interval are shown. Statistics are from Hurricane Danny (gray) from 2- to 5-km altitude and Hurricane Bret (black) from 1- to 5-km altitude.

The optimal time interval for curve fitting was examined at 30-min intervals (containing ~5 WSR-88D volumes), up to the full 5 h of the available datasets. Results from this sensitivity test are shown in Fig. 6. For Hurricane Danny, the mean distance between centers was near 2 km, even with a few volumes of data, but converged to 1.5 km as the time interval was increased. The standard deviation decreased from ~1.6 km to below 1 km, with a noticeable decrease above the 2-h time interval. The effect of fitting over longer time scales primarily affects the spread of the data, with a longer

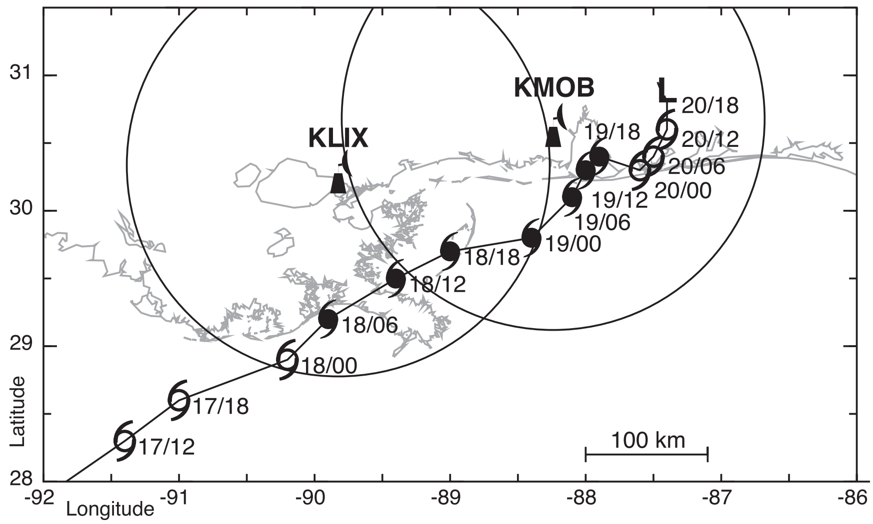

Fig. 7. The official best track of Hurricane Danny (line) near landfall on 19 Jul 1997. Filled and unfilled hurricane symbols represent hurricane and tropical storm intensity, respectively, and "L" represents the downgrade to tropical depression. Numbers next to each symbol indicate the day/time of the position. Circles show 174-km Doppler range of KLIX and KMOB radars.

time interval resulting in a smoother curve fit and fewer outliers. For Hurricane Bret, the method performs well even with only 30 min of data, and mean and standard deviation decreases slightly up to the 2-h time interval. The results are essentially unchanged for longer time intervals. This suggests that accumulation of statistics over longer time intervals is beneficial for weaker storms, but may not significantly degrade the results for the more intense storms. An upper limit of 6 h for curve fitting appears to be a reasonable maximum, as small-scale motion and storm changes may begin to become blurred by the polynomial fit beyond this range.

5. Results with Hurricanes Danny (1997) and Bret (1999)

Hurricane Danny was a slow-moving category-1 storm on the Saffir–Simpson scale that made landfall in Mobile Bay on 19 July 1997. Danny formed in the Gulf of Mexico on 16 July and single-Doppler radar coverage of its development is available over much of its life cycle before and after landfall. The storm was observed simultaneously by the Slidell, Louisiana (KLIX), and Mobile, Alabama (KMOB), WSR-88D units for over 5 h at viewing angles almost perpendicular to each other as shown in Fig. 7. Hurricane Bret made landfall as a category-3 storm along the Texas coast on 23 August 1999. Bret was simultaneously observed by the WSR-88D units at Corpus Christi (KCRP) and Brownsville (KBRO) as it weakened from a category-4 storm prior to landfall (Fig. 8). Bret was significantly stronger and more organized than Danny, and had a track that passed between the two radars, providing both a different meteorological situation and radar geometry for testing of the algorithms described herein.

The analyses were performed using CAPPIs from 1- to 5-km altitude from all available radar volumes during 5-h periods for both storms. Radar data coverage above 5 km was limited and therefore not considered. Figure 9 shows the approximate height of the lowest elevation radar

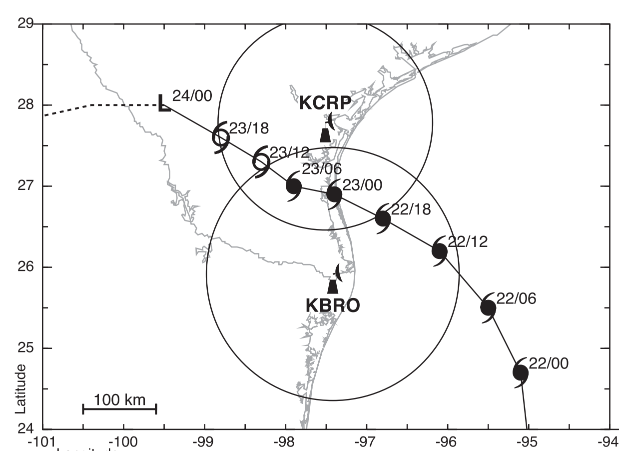

Fig. 8. The official best track of Hurricane Bret (line) near landfall on 23 Aug 1999. Symbols as in Fig. 7. Circles show Doppler range of KCRP and KBRO radars (147 and 174 km, respectively).

beam at the estimated TC center during the 5-h period for both Hurricane Danny and Bret (assuming normal beam propagation in standard atmosphere and the effect from earth curvature). When the height of the lowest elevation radar beam exceeds a grid level, the radar data were extrapolated downward when the CAPPI altitude was within 1 km of the actual radar observations, assuming that the radar volume partially sampled this altitude because of beam spreading. The beam was too high to obtain meaningful results from KMOB at 1-km altitude for most of the analysis time and was therefore not used in the statistical comparisons.

a. Hurricane Danny

The analysis focused on the comparisons between retrieved circulation centers from the two radars during the period between 1600 and 2100 UTC 18 July 1997. KLIX and KMOB observed the storm from a near-perpendicular angle as the TC tracked near the coast (Fig. 10). The GBVTD-simplex algorithm was initialized using 16 center guesses in a 12 km × 12 km box near the TC center rough estimate at each time, and centers for rings of 1-km annulus between 10- and 30-km radii were calculated. The Fourier fit was restricted to azimuthal wavenumbers 0 and 1, and the optimal NORM and SCL weights derived from the sensitivity tests were used.

Figure 10 shows a sample 2-km CAPPI image of the reflectivity and Doppler velocity from KLIX radar at 1802 UTC and KMOB radar at 1804 UTC. Several interesting features can be noted: the strong wavenumber-1 asymmetry on the south side of the TC, the lack of scatterers in the eye, and the presence of a partial double eyewall. Danny therefore not only provides a good track to allow for intercomparison, but also exhibits several storm structures that make it a challenging test case for center-finding algorithms.

The axisymmetric tangential wind versus radius retrieved by GBVTD-simplex from KLIX and KMOB radars at this time is plotted in Fig. 11. The primary wind maximum can be estimated easily by KLIX retrievals at 1 km, but is more difficult to discern at the higher levels. In general, the radial gradient of tangential wind in Hurricane Danny is weak, like the idealized example shown in Fig. 2a. A secondary wind peak is weakly evident at 1-km altitude from KLIX, but Danny was too far away from KMOB to resolve the 1-km-altitude winds. The KLIX 1-km wind profile is similar to the idealized example shown in Fig. 2b.

Figure 12 shows the high-resolution tracks derived using the original GBVTD-simplex method and the objective statistical center method. Because of slight differences in the starting time of each corresponding volume scan between KMOB and KLIX, only general agreement between the selected circulation centers can be inferred from this plot. The discrepancy between the KMOB and KLIX centers in the original method is improved significantly by the new method. The tracks appear to be more in agreement at all levels using the improved center method, with the primary discrepancy occurring near the beginning and end of the 5-h period. This is due to the mismatched beam resolution and beam altitude of the radars, limited data coverage, and weak constraints on the polynomial curve fits near the beginning and end of the analysis period (cf. Fig. 9).

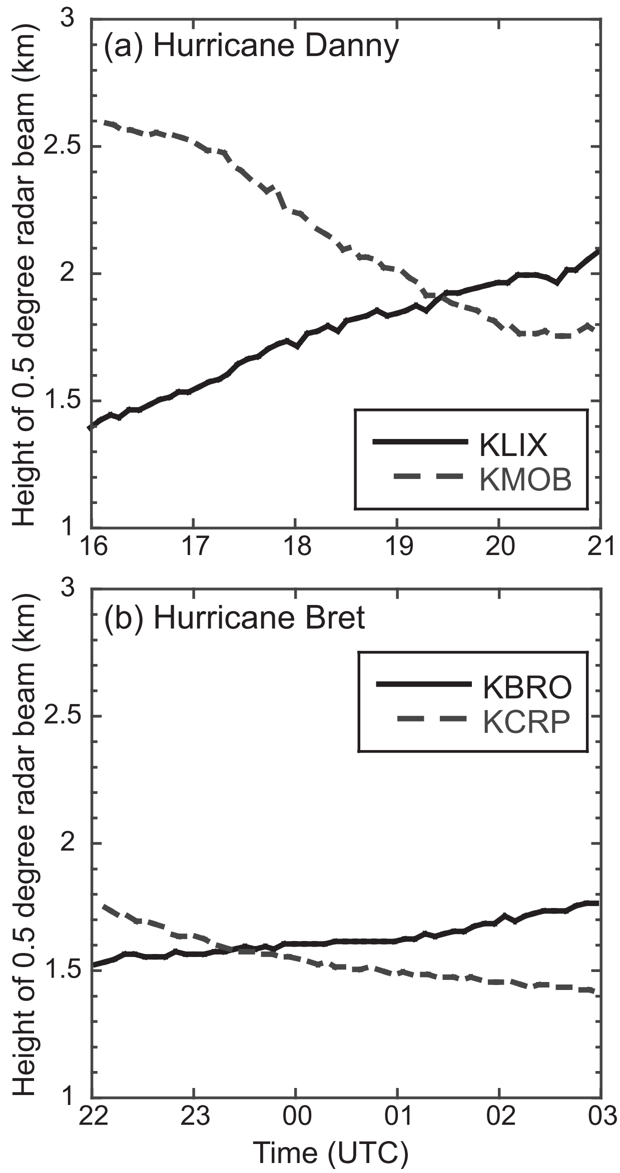

FIG. 9. Approximate height of the 0.5° elevation radar beams at center of (a) Hurricane Danny and (b) Hurricane Bret during the analysis period. The height was calculated assuming normal propagation of the beam.

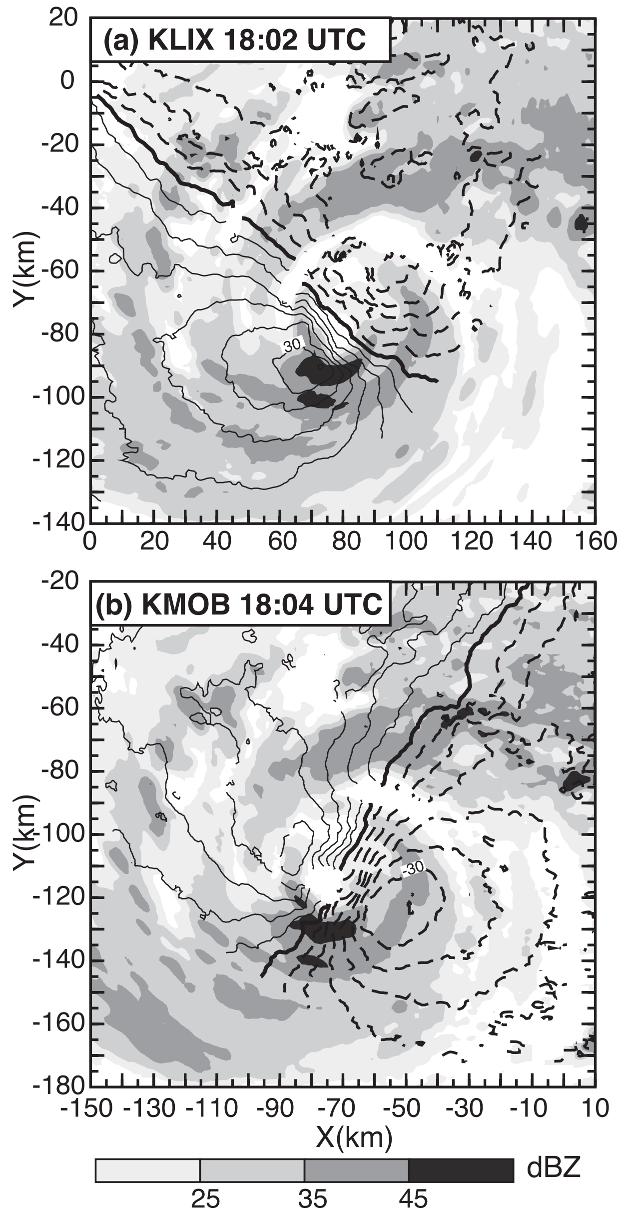

FIG. 10. Reflectivity and Doppler velocity at 2 km of Hurricane Danny from (a) KLIX radar at 1802 UTC and (b) KMOB radar at 1804 UTC. Grayscale shading indicates reflectivity and lines indicate 5 m s^{-1} Doppler velocity contours, with dashed contours indicating negative radial velocities. The X and Y Cartesian distances are in kilometers relative to radar locations.

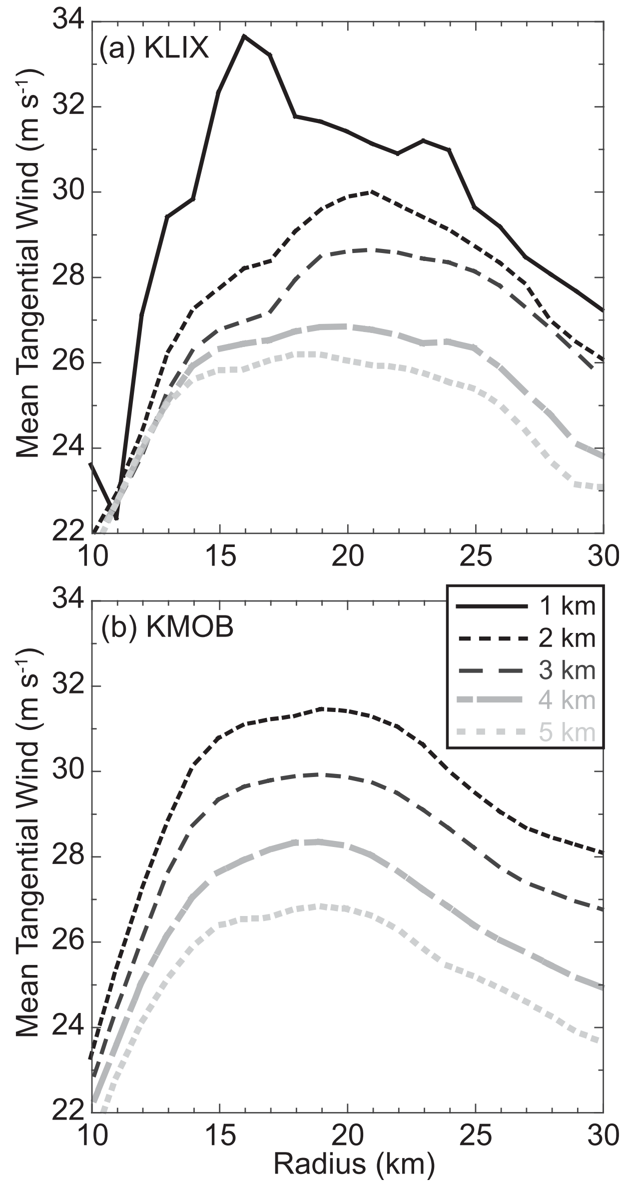

FIG. 11. Radial profiles of axisymmetric tangential wind derived from the GBVTD-simplex algorithm from 1- to 5-km altitude for Hurricane Danny at (a) 1802 UTC from KLIX radar and (b) 1804 UTC from KMOB radar. The 1-km data from KMOB are not available because of the range from the radar.

Statistical evidence of the agreement between the KLIX and KMOB centers derived using the objective statistical center method is shown in Table 2 by linearly interpolating the center locations to 1-min intervals and comparing the proximity of center estimates numerically. The mean distance between center estimates for the improved method is 1.5 km, representing a 50% improvement over the original GBVTD-simplex method. Despite the weakening tangential wind gradient at higher levels the mean distance using this method stays remarkably stable, while the mean and maximum distance in the original method steadily increases with altitude. At 5 km, some of the original center estimates were 21.7 km apart, yet the improved method has a maximum distance of only 4.6 km. M11 selected centers subjectively for this case by reviewing the GBVTD-simplex output and comparing the information from both radars. It is noted that distance statistics from the subjectively

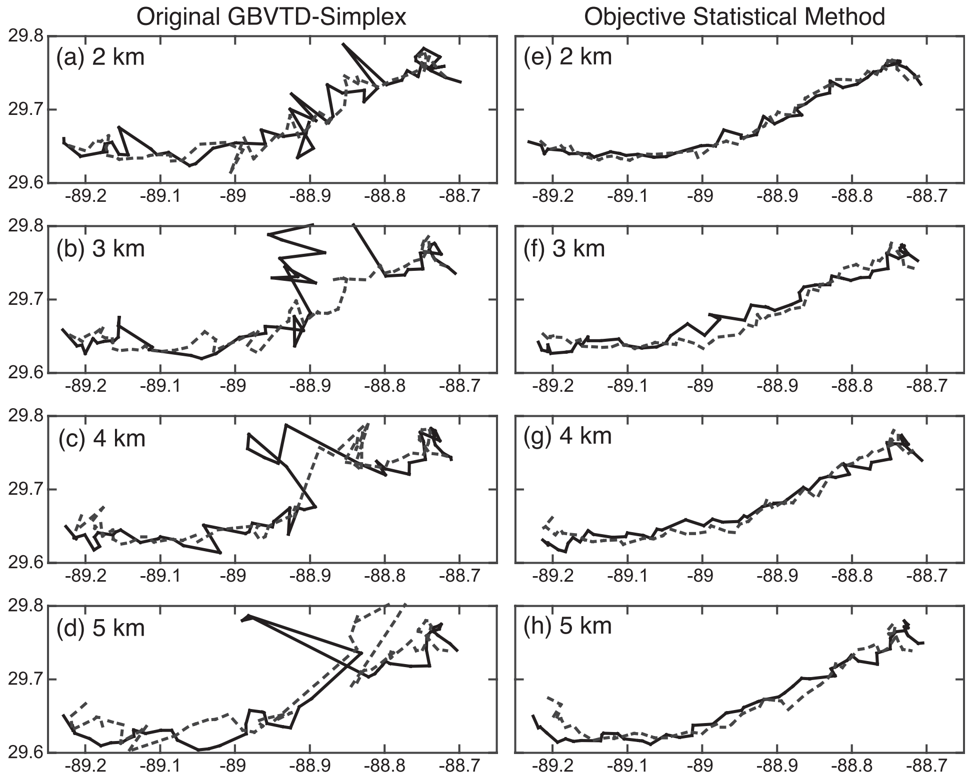

FIG. 12. Comparison of Hurricane Danny's circulation centers. (a)–(d) Centers from the original GBVTD-simplex algorithm at heights 2–5 km, from top to bottom, respectively. (e)–(h) Centers from the objective statistical center-finding method. Solid black line indicates track derived from KLIX radar, and dashed gray line indicates track from KMOB radar.

selected centers are comparable to those selected by the objective statistical method presented here (cf. Fig. 3 and Table 1 in M11). M11's effort took significantly longer than the few minutes the objective statistical center method took to run, however.

The centers were also compared with those derived from dual-Doppler analyses using the method described in Marks et al. (1992). The simplex search parameters were set the same as those in the GBVTD-simplex method, but the dual-Doppler-derived wind field was used to determine the axisymmetric tangential wind (M11). The dual-Doppler simplex results were then processed using the objective statistical center-finding method analogously to the single-Doppler results for comparison. A comparison of the differences between the dual-Doppler-derived centers and GBVTD centers from KLIX and KMOB is shown in Table 3. The distances between the dual-Doppler- and single-Doppler-derived centers are on the order of 2 km averaged over 2–5-km altitude. This is higher than the statistics obtained from comparing the single-Doppler centers with each other, but the RMW and tangential wind compare well, with mean and RMS values below 1 km and 1 m s^{-1}, respectively. Though the dual-Doppler wind field is presumably more robust than the single-Doppler case, the dual-Doppler-simplex center-finding method suffers from some of the same problems in identifying the center as the GBTVD-simplex. Weak

TABLE 2. Statistics on distance between independent single-Doppler circulation center estimates from KLIX and KMOB radars for Hurricane Danny (1997) over heights 2–5 km. All statistics are in kilometers.

	Min	Max	Mean	Median	RMS	Std dev
			Original GBVTD-simplex			
2 km	0.2	6.2	2.2	1.9	2.5	1.2
3 km	0.2	11.4	3.0	2.0	4.0	2.6
4 km	0.1	15.1	3.0	1.9	4.5	3.4
5 km	0.1	21.7	3.7	2.1	5.6	4.2
Total	0.1	21.7	3.0	2.0	4.3	3.1
			Objective statistical center-finding method			
2 km	0.0	3.0	1.1	0.9	1.3	0.6
3 km	0.2	4.6	1.6	1.7	1.8	0.8
4 km	0.1	3.7	1.4	1.2	1.5	0.7
5 km	0.2	4.5	1.8	1.7	2.0	0.9
Total	0.0	4.6	1.5	1.4	1.7	0.8

TABLE 3. Statistics on distance, RMW, and maximum axisymmetric tangential wind (VT) between single-Doppler circulation center estimates from KLIX and KMOB radars for Hurricane Danny (1997) with dual-Doppler circulation centers from 2 to 5 km. Distance and RMW statistics are in kilometers, and VT statistics are in meters per second.

	KLIX distance	KLIX RMW	KLIX VT	KMOB distance	KMOB RMW	KMOB VT
Min	0.1	−3.0	−3.2	0.5	−2.1	2.2
Max	8.0	8.0	2.1	10.3	9.0	−2.2
Mean	2.2	0.9	−0.9	2.8	0.7	0.3
Median	2.0	1.0	−0.9	2.8	0.6	0.3
RMS	2.6	1.3	1.2	3.0	1.3	0.9
Std dev	1.3	1.0	0.8	1.0	1.1	0.8

tangential wind gradients and missing data lead to ambiguities in the circulation center much like the single-Doppler results, and the difference in radar scan times between KLIX and KMOB can add error to the center estimates. The dual-Doppler centers are considered to be a useful reference, but not necessarily the "ground truth." Essentially, Danny's centers obtained from KMOB and KLIX independently are consistent with those obtained from the dual-Doppler radar analysis.

Analysis of the axisymmetric tangential wind and RMW during this time period is shown in Fig. 13. The improved method primarily improves the RMW agreement between the two radars to within 1–2 km of each other. Some large differences of ~5 km did occur, but were less frequent than in the original algorithm. The apparent inverse oscillation between the derived tangential winds is likely due to aliasing in the GBVTD formulation as discussed in M11. It is speculated that this oscillation is the result of a wavenumber-2 radial wind asymmetry aliased into the axisymmetric tangential wind (W. C. Lee et al. 2006), which manifests as a oppositely signed offset because the viewing angles from KMOB and KLIX are nearly perpendicular.

b. Hurricane Bret

A 5-h period was selected for analysis from 2200 UTC 22 August to 0300 UTC 23 August. Results from the two radars are shown in Fig. 14 and Table 4. The original GBVTD-simplex method performed much better for Bret than for Danny probably because of a better-defined circulation in the category-3–4 storm than in the weaker category-1 storm. Centers derived using the improved method were qualitatively the same as the original algorithm but removed some outliers. The objective statistical method does show an improvement in the mean distance of 13%, largely because of the removal of the outliers and impact at higher altitudes. Bret's track shows a discrepancy at the edges of the Doppler range similar to Danny's.

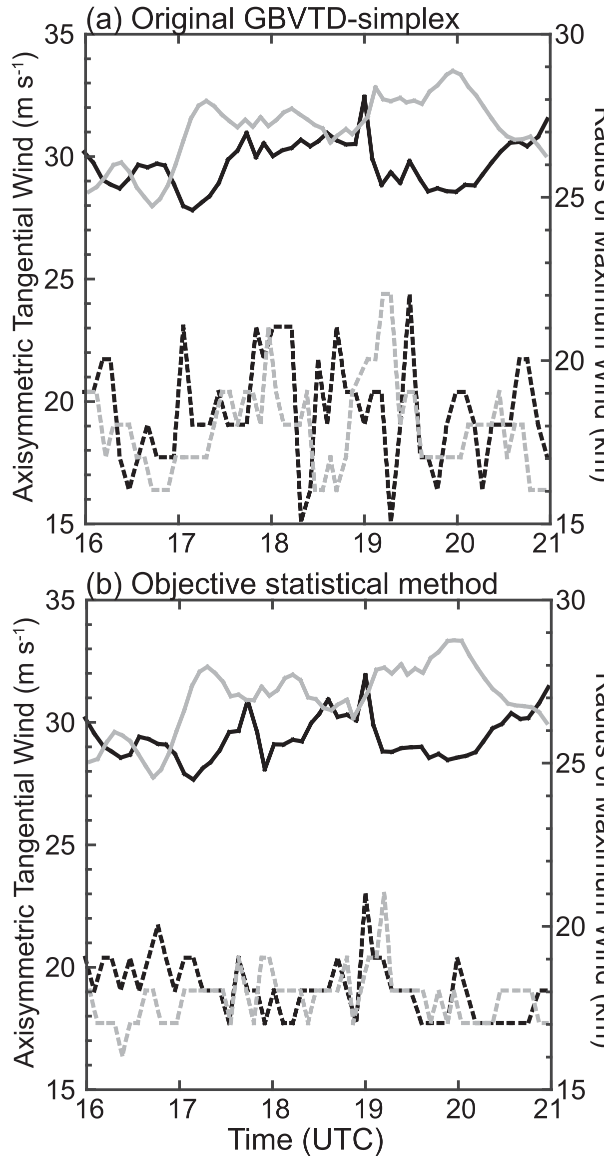

FIG. 13. Comparison of derived storm characteristics for Hurricane Danny at 2 km using (a) original GBVTD-simplex method and (b) objective statistical center-finding method. Solid line shows GBVTD-retrieved maximum axisymmetric tangential wind, and dashed line shows RMW from KLIX (black) and KMOB (gray) radars.

The similarity of the results between the original and improved methods suggests that the characteristics of Bret were more forgiving for center estimation than the Danny case. Figure 15 shows two derived radial profiles of axisymmetric tangential wind at 0000 UTC 23 August. The peak winds are more pronounced than those in Danny, even at higher levels, and the original method therefore had very few problems discerning the RMW and selecting consistent centers. The objective statistical method reflects this in a low variance of the

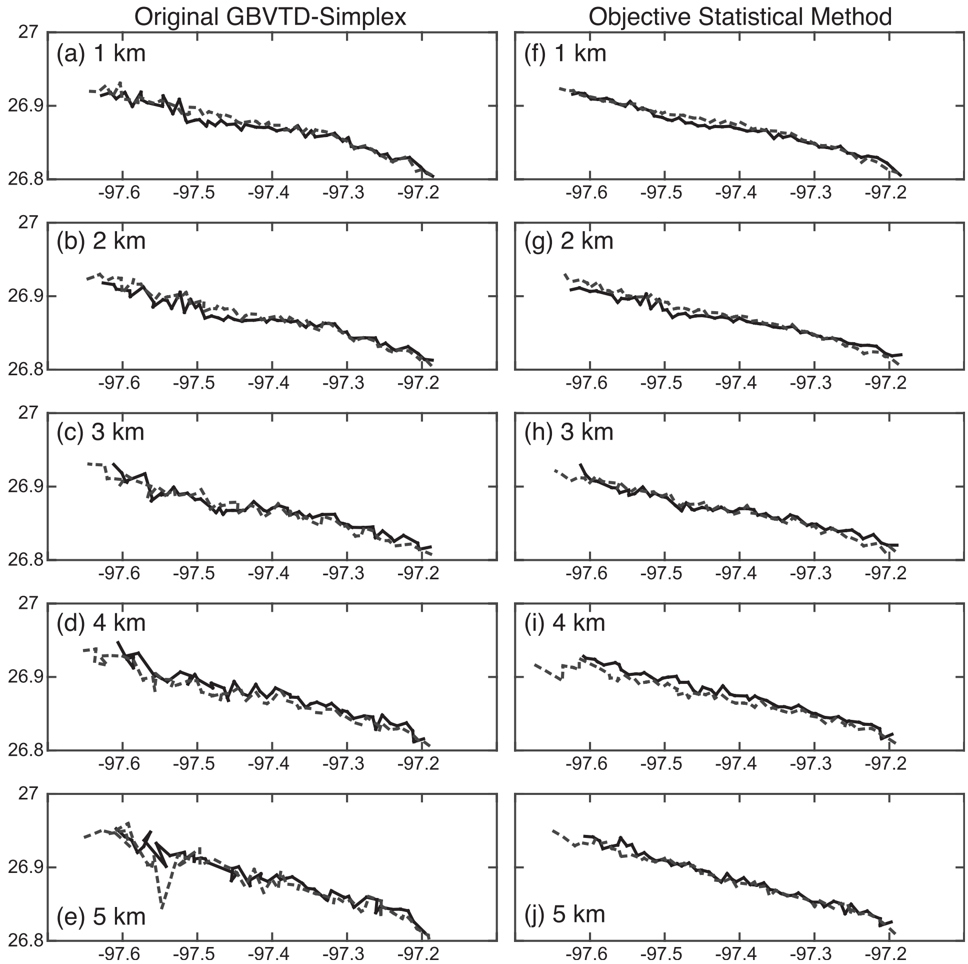

FIG. 14. Comparison of Hurricane Bret's circulation centers. (a)–(e) Centers from the original GBVTD-simplex algorithm from heights 1–5 km, from top to bottom, respectively. (f)–(j) Centers from the objective statistical center-finding method. Solid black line indicates track derived from KBRO radar, and dashed gray line indicates track from KCRP radar.

RMW curve fit. Analysis of the axisymmetric tangential wind and RMW over time shows a strong correlation between the two radar retrievals in Fig. 16. Both methods show a consistent RMW during the early period, with increasing ambiguity as the circulation is disrupted over land. A constant difference in the mean tangential winds derived from two WSR-88Ds is evident for Bret, which contrasts with the oscillatory difference in the Danny case. The constant offset in the Bret observations is believed to result from an unresolved cross-beam mean wind component as discussed in Harasti et al. (2004).

6. Uncertainty estimates

The datasets for Danny and Bret allow for the comparison of objectively determined individual circulation center estimates and can be used to evaluate the uncertainty of the method. By including centers from all heights and times, a large sample of centers can be obtained to construct histograms of the distance between the single-Doppler circulation centers. Figure 17a shows the histogram of distances between centers for Hurricane Danny. The distribution has a clear shift to lower values when the objective statistical center-finding method was applied, with a noticeable reduction in the tail of the distribution. Assuming this sample represents the uncertainty of the circulation center estimates, the distribution resulting from the use of the method described in this paper yields a mean of 1.5 km, with a standard deviation of 0.8 km. Thus, a 95% confidence upper bound for the uncertainty is 3.1 km for Danny, and a target uncertainty of 2 km can be achieved with a ~75% confidence level. Comparisons with the objectively determined

TABLE 4. Statistics on distance between independent single-Doppler circulation center estimates from KBRO and KCRP radars for Hurricane Bret (1999) over heights 1–5 km. All statistics are in kilometers.

	Min	Max	Mean	Median	RMS	Std dev
Original GBVTD-simplex						
1 km	0.2	2.7	1.1	1.1	1.2	0.5
2 km	0.2	3.5	1.1	0.9	1.3	0.7
3 km	0.1	2.9	1.0	0.9	1.1	0.5
4 km	0.1	4.8	1.4	1.1	1.6	0.9
5 km	0.1	8.3	1.5	1.1	2.0	1.2
Total	0.1	8.3	1.2	1.0	1.5	0.8
Objective statistical center-finding method						
1 km	0.4	1.6	1.0	1.0	1.0	0.2
2 km	0.2	2.5	1.1	0.9	1.2	0.5
3 km	0.2	3.3	0.9	0.7	1.0	0.6
4 km	0.2	6.2	1.4	1.0	1.7	1.0
5 km	0.1	3.9	1.1	0.9	1.5	0.9
Total	0.1	6.2	1.1	0.9	1.3	0.7

dual-Doppler centers suggest that the 95% upper confidence bound may be closer to 4 km (see Table 3). However, the differences in the way the centers are derived may account for some of this discrepancy. The probability distribution for Hurricane Bret is shown in Fig. 17b. There is less of an improvement from the original method to the objective statistical center-finding method, but there is a discernible shift in the distribution. The sample mean for Bret is 1.1 km with a standard deviation of 0.7 km. This yields a 95% confidence upper bound of 2.5 km, with an ~90% confidence level for the target uncertainty of 2 km. These results are consistent with the center uncertainty estimated by LM00 for Typhoon Alex.

One may conclude from these results that the uncertainty is proportional to the intensity and structure of the TC. Strong TCs with a well-defined RMW allow for better estimation of the circulation center. Since the error in the wavenumber-1 magnitude is a function of both center displacement and TC intensity, there is a similar absolute wind error for both Danny and Bret. The increase in center precision is offset by the increase in intensity, so that the relative wind error decreases but the absolute error remains the same. Based on LM00's analytic TC studies, the respective center uncertainties would yield the same average error of ~3 m s^{-1} in the magnitude of the GBVTD-retrieved wavenumber-1 asymmetry for Danny and Bret. Given an estimated 10 m s^{-1} wavenumber-1 component, this would yield an approximate magnitude error of 30%, and possible bias in phase.

Histograms for the uncertainty in RMW and axisymmetric tangential wind are presented in Figs. 18a,b. The

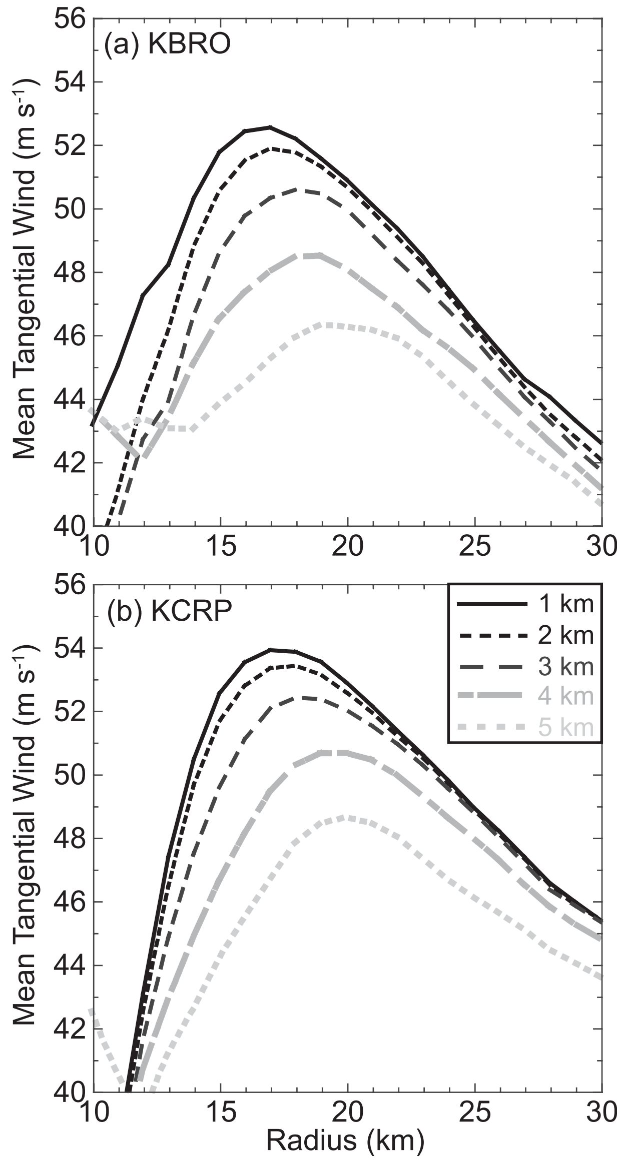

FIG. 15. Radial profiles of axisymmetric tangential wind derived from the GBVTD-simplex algorithm from 1- to 5-km altitude at (a) 0000 UTC 23 Aug from KBRO and (b) 2357 UTC 22 Aug from KCRP radar.

mean difference in RMW was 0.7 and 1.0 km, with standard deviations of 0.9 and 0.8 km, for Bret and Danny, respectively. This is comparable to the 1-km CAPPI grid resolution and the 1-km ring width used for center finding. For the tangential wind, the mean difference was 2.3 and 1.3 m s^{-1} for Bret and Danny, respectively, with standard deviations of 0.5 and 1.0 m s^{-1}. These values correspond to a less than 5% error in both the RMW and axisymmetric tangential wind for these TCs, and are comparable to the differences with the dual-Doppler-derived values in the Danny case. Thus,

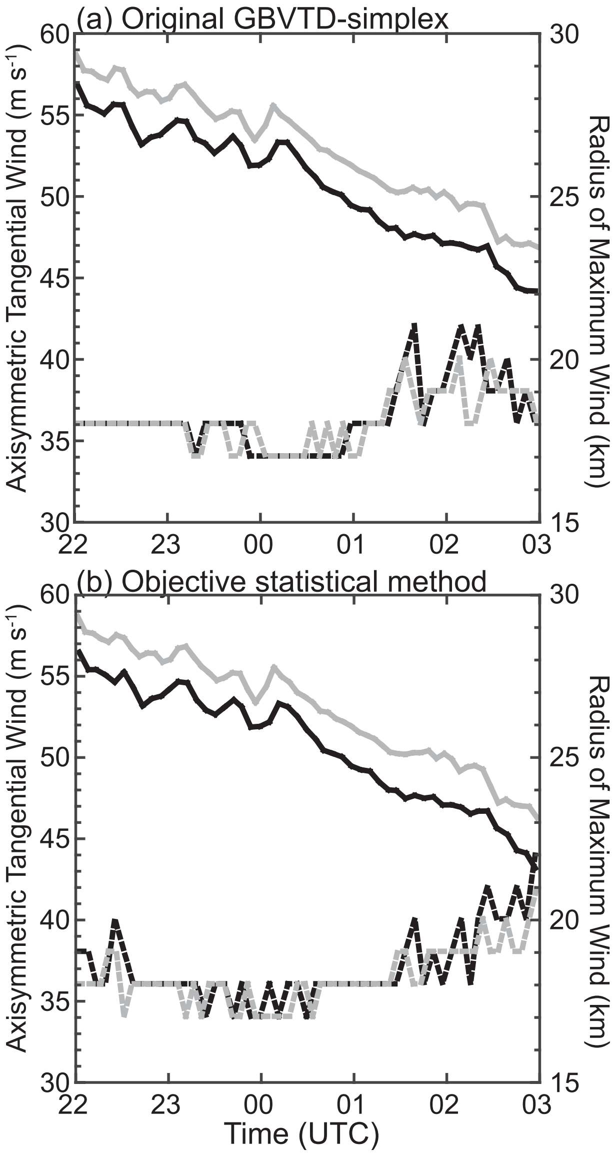

FIG. 16. Comparison of derived storm characteristics for Hurricane Bret at 2 km using (a) original GBVTD-simplex method and (b) objective statistical center-finding method. Solid line shows GBVTD-retrieved maximum axisymmetric tangential wind, and dashed line shows RMW from KBRO (black) and KCRP (gray) radars.

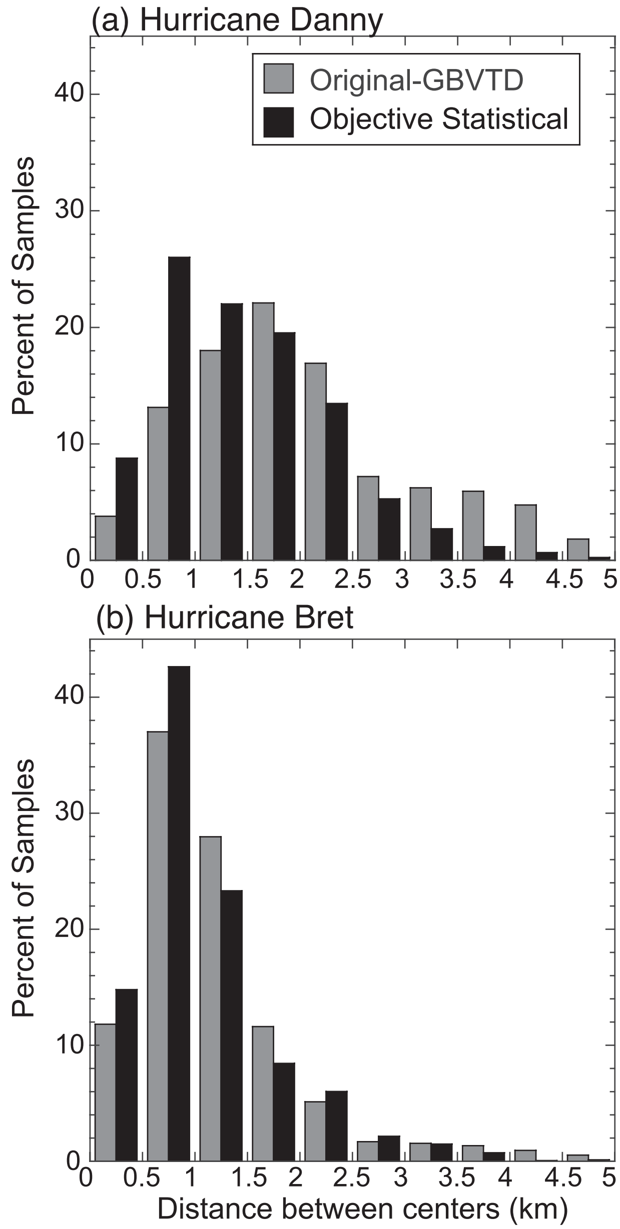

FIG. 17. Histogram of distances between independently determined centers for (a) Hurricane Danny and (b) Hurricane Bret for 5-h analysis time period from heights of 2–5 km. Bars show percentage of center differences in 500-m bins for the original GBVTD-simplex algorithm (gray) and objective statistical center-finding method (black).

even without further wind reconstruction, reasonably accurate TC characteristics can be obtained with this method. This information could augment wind radii and intensity estimates provided by Dvorak techniques, aircraft reconnaissance, and H*Wind (Powell et al. 1998) products. The high temporal and a spatial resolution of the wind field, accompanied by uncertainty estimates, could also provide useful data for assimilation (Zhao et al. 2012) or validation of numerical weather prediction (J. L. Lee et al. 2006).

7. Summary

M11 showed that the continuity of spatial and meteorological characteristics over several hours improved TC center estimates from a single-Doppler radar using the subjective statistical center-finding method. The proposed objective statistical center-finding method utilizes these characteristics to automatically retrieve

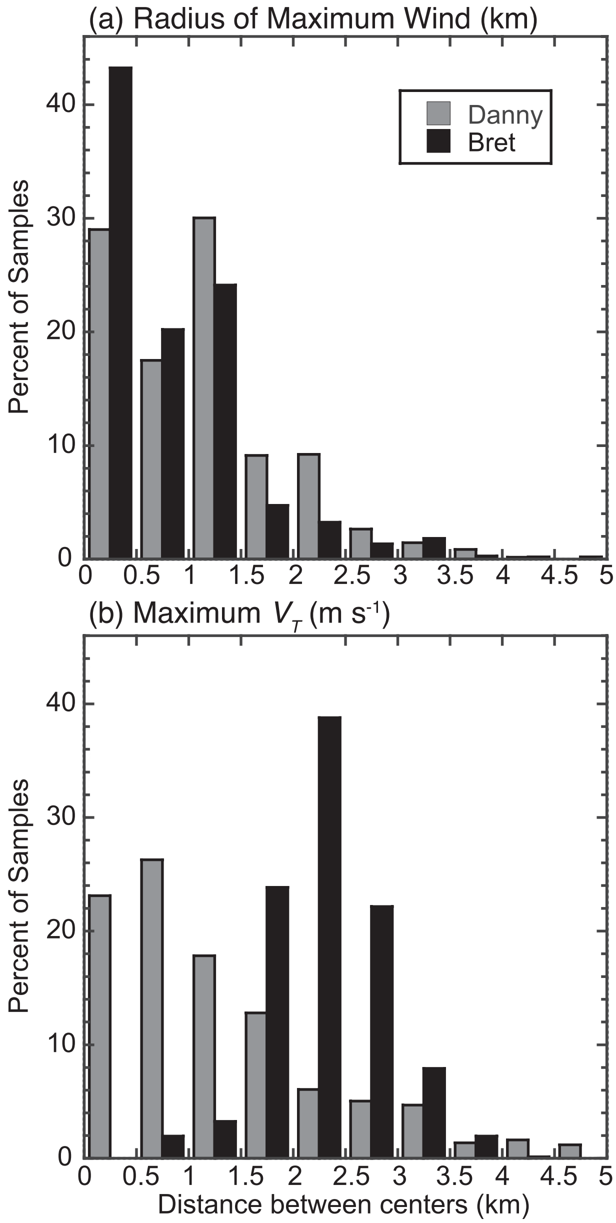

FIG. 18. Histograms of absolute difference between independent estimates of (a) radius of maximum wind and (b) maximum axisymmetric tangential wind. Results are shown for Hurricane Bret (black bars) and Hurricane Danny (gray bars).

the centers in significantly less time than the subjective statistical center-finding method, allowing for efficient postanalysis research refinement of TC centers. The case studies presented show that the center uncertainty is related to the intensity and structure of the TC in addition to the intrinsic assumptions in the GBVTD formulation and data distribution/coverage. For Hurricane Danny (category 1), the mean center uncertainty using the improved method was 1.5 km, and for Hurricane Bret (category 3) the mean center uncertainty was 1.1 km. These values represent 50% and 10% improvements, respectively, over the original GBVTD-simplex algorithm. This spatial accuracy corresponds to less than 5% error in the retrieved RMW and axisymmetric tangential wind, and ~30% error for a typical wavenumber-1 asymmetry.

This method has been incorporated into the Vortex Objective Radar Tracking and Circulation (VORTRAC) program in operational use at the National Hurricane Center (Harasti et al. 2007). The high spatial and temporal resolution estimates of TC properties obtained with Doppler radar can provide valuable information to forecasters. In a real-time operational mode, the method can use the results of the previous radar volume to initialize the GBVTD-simplex search for the subsequent volume. The polynomial curve fits can be recalculated as new radar volumes become available and improve the quality of the track the longer the TC is in Doppler range. This technique is limited by the need for adequate Doppler radar coverage, but even the most rapidly moving storms typically have several hours of Doppler radar data before landfall. Several significant TCs have traveled parallel to the coast for two or more days prior to landfall and within range of current WSR-88D coastal units (McAdie et al. 2009). Radars in tropical island locations can also provide valuable wind information as a TC impacts the island or for numerical weather prediction initialization in advance of a continental landfall.

One of the remaining major challenges is to properly initialize the GBVTD-simplex algorithm when a TC is located beyond and/or just enter the Doppler velocity range of a coastal radar where a complete Doppler velocity dipole signature is not available for accurate estimation of TC circulation center. It is proposed to include reflectivity-based center-finding algorithms—for example, the tropical cyclone eye tracking algorithm (TCET; Chang et al. 2009)—to estimate TC centers before the Doppler velocity-based center-finding algorithm can be effective. Chang et al. (2009) illustrated TCET produced comparable results with those deduced from the GBVTD-simplex algorithm. However, both the reflectivity-based and the Doppler velocity-based center-finding algorithms will not be effective when a TC eyewall is influenced by steep terrain and/or after landfall when the primary circulation disintegrates.

Future research will also examine the possibility of using vertical continuity as an additional constraint in center estimation. This is a complicated problem since vortex tilt depends significantly on the environmental wind, which is not fully resolved by GBVTD. Techniques such as hurricane volume velocity processing (HVVP; Harasti 2003) and generalized VTD (GVTD; Jou et al. 2008) may help to resolve this and improve the underlying wind retrieval used in the algorithm. Additional case studies will also be examined to improve the method. Tropical storms with weak tangential wind gradients and ill-defined centers, TCs exhibiting strong asymmetries, and unique multi-Doppler coverages similar to that provided by Danny and Bret will provide additional scenarios with which to test the technique.

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