The Gust-Front Detection and Wind-Shift Algorithms for the Terminal Doppler Weather Radar System

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ABSTRACT

The Federal Aviation Administration's Terminal Doppler Weather Radar (TDWR) system was primarily designed to address the operational needs of pilots in the avoidance of low-altitude wind shears upon takeoff and landing at airports. One of the primary methods of wind-shear detection for the TDWR system is the gust-front detection algorithm. The algorithm is designed to detect gust fronts that produce a wind-shear hazard and/or sustained wind shifts. It serves the hazard warning function by providing an estimate of the wind-speed gain for aircraft penetrating the gust front. The gust-front detection and wind-shift algorithms together serve a planning function by providing forecasted gust-front locations and estimates of the horizontal wind vector behind the front, respectively. This information is used by air traffic managers to determine arrival and departure runway configurations and aircraft movements to minimize the impact of wind shifts on airport capacity.

This paper describes the gust-front detection and wind-shift algorithms to be fielded in the initial TDWR systems. Results of a quantitative performance evaluation using Doppler radar data collected during TDWR operational demonstrations at the Denver, Kansas City, and Orlando airports are presented. The algorithms were found to be operationally useful by the FAA airport controllers and supervisors.

1. Introduction

A gust front is the region of rapid wind increase or shear at the leading edge of the cold-air outflow from a thunderstorm. Wind shear and turbulence along the gust front are potentially hazardous to landing or departing aircraft. The change of wind speed and direction in the terminal area associated with gust fronts, as well as synoptic fronts, is also a cause of significant air traffic delay and excess fuel consumption, due to time-costly runway configuration changes. Because of this, the detection of gust fronts and wind shifts in the terminal environment is an important function of the Federal Aviation Administration's (FAA) Terminal Doppler Weather Radar (TDWR) system. The TDWR system was motivated primarily by air safety concerns asso-

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associated with low-altitude wind shear. The system relies on automated Doppler radar-based detection of hazards in the terminal area and provides warnings of hazards to pilots (Evans and Turnbull 1989).

Two separate algorithms have been developed to detect most gust-front hazards and to forecast their movement. The gust-front detection algorithm (GFDA) detects the locations of gust fronts in Doppler velocity fields and produces hazard warnings. These warnings identify the regions of strong convergent air motions in the airport vicinity and provide estimates of the wind-speed gains pilots might expect upon penetration of the gust front. The wind-shift algorithm (WSA) uses the GFDA detection and propagation information, and a single elevation scan of Doppler velocities, to estimate the mean wind speed and direction behind the front. During the Classify, Locate, and Avoid Wind Shear (CLAWS) project (McCarthy et al. 1986), it was determined that a 20-min forecast of a wind shift at the airport was a useful product for air traffic management. This information gives air traffic controllers time to redirect aircraft and configure arrival and departure runways to minimize the impact of the wind shift on airport capacity.

This paper documents the design of the gust-front detection and wind-shift algorithms to be fielded during the initial TDWR system deployment. Section 2 reviews some of the development of the algorithms and describes the various logical steps involved in the analysis of the Doppler velocity data to detect the hazards, and forecast the wind shifts, associated with gust-front passage. Section 3 describes the wind estimation technique of the wind-shift algorithm. Section 4 contains a comprehensive performance evaluation of both GFDA and WSA products and discusses preprocessing of the data prior to algorithm invocation.

It is important for the reader to realize that these algorithms were designed using methodologies that would produce real-time results on the computing systems available during the development time period (early 1980s). Further, there was a desire for the number of false detections to be kept very low. Other factors, including documentation deadlines, testing deadlines, and database availability during the earliest development and testing phases, also affected the methodologies chosen for the algorithms. The limitations of these foundational methodologies are discussed in section 5.

2. The gust-front detection algorithm (GFDA)

The gust-front detection algorithm (GFDA) was initially designed and developed by Uyeda and Zrnić (1986). This algorithm has the capability of detecting, within a field of Doppler radar velocities, the radial convergence lines that characterize gust fronts. With limited testing, Uyeda and Zrnić showed that the algorithm can locate and track strong gust fronts that commonly occur in Oklahoma in spring. The algorithm has since been modified from its semiautomatic research state to that of a fully automated algorithm for operational use.

Enhancements added prior to real-time testing during the 1987 TDWR experiment in Denver, Colorado, included the vertical association of gust-front signatures using two low-altitude elevation scans to reduce false alarms, as well as a technique to supply horizontal wind estimates ahead of and behind detected gust fronts. The report by Witt and Smith (1987) highlights these enhancements and documents other refinements to the GFDA, such as threshold selection.

Another iteration of GFDA development followed field tests in the Denver area during 1987. Data preprocessing was improved by including a sophisticated velocity dealiasing scheme (Eilts and Smith 1989). Algorithm improvements included adding a technique to mitigate ground clutter-induced errors in gust-front detections, better representation of the gust fronts, validity checking of the wind estimates, and a perpendicular wind estimate as an alternate wind estimation scheme (Witt et al. 1989).

a. Pattern recognition

The GFDA relies on the identification of the main attribute that gust fronts possess in Doppler velocity fields, that is, lines of radial convergence. Detection of other attributes of gust fronts observed by Doppler radar, such as azimuthal shear and reflectivity thin lines, are not part of the initial TDWR algorithm but may be added in future system upgrades.

Figure 1 shows a sample radial of velocity data through a gust front. The algorithm begins its pattern recognition technique by smoothing the radial velocity data in range using a nine-point running average. Using the smoothed data, the algorithm searches along radials for runs of decreasing velocity, which characterize radial convergence, to identify "shear segments." However, there is often substantial point-to-point variation of the smoothed radial velocity in range (see highlighted box on Fig. 1). Therefore, when searching for convergence, a seven-point look-ahead procedure allows for comparison of a particular velocity value with the seven adjacent velocities farther in range (Fig. 2). The algorithm chooses the radial velocity within the group of seven that is numerically closest to, but less than or equal to, the velocity in question (see highlights on Fig. 2). Subsequent iterations compare the accepted radial velocity with the next seven values in range. A shear segment terminates if an increase in radial velocity occurs over seven consecutive points in range.

The peak radial shear (defined as the maximum shear over a distance of approximately 1 km within the shear segment) and the difference between the beginning and ending velocity ($\Delta V$) are compared to minimum thresholds to determine whether a shear segment is saved. The recommended values for these
shear locations. If there are fewer than five segments in any one feature, the feature is discarded. Furthermore, the feature is discarded if its length (defined as the distance between end points of the feature) is less than a threshold length (5 km).

As a validity check on detected features, a user selectable feature suppression window can be activated. These windows are used primarily to eliminate recurring false feature detections located in regions with residual ground clutter contamination. Features whose centroids lie within the specified windows are discarded. The feature centroid is the average of the peak-shear locations \((x, y)\) of all its shear segments. Upon completion of this validity check, features in close proximity are combined.

c. Vertical association

Witt and Smith (1987) found a large reduction in algorithm false detections when vertical association of features is required in the GFDA. As a result, the initial TDWR GFDA algorithm uses two low-elevation-angle scans (typically 0.5° and 1.0°) to determine if gust fronts are present.

For two features detected at different elevation scans to satisfy the requirements of vertical association, it is necessary for the centroid of one feature to be within the “vertical continuity box” of the other feature. The thresholds are 2.0 m s\(^{-1}\) km\(^{-1}\) and 5 m s\(^{-1}\), respectively. These values were selected to maximize the detection and forecasting of gust fronts that produce sustained wind shifts, while keeping the number of false detections low.

It should be noted that the value of \(\Delta V\) is not the difference between the maximum and minimum velocities within the shear segment. As part of the look-ahead procedure, the beginning and ending locations of the shear segment will usually not correspond with the locations of the maximum and minimum velocities of the segment (e.g., see “E” denoted in Fig. 1). While this may seem like an oddity, it was found to be useful during algorithm testing. In addition, test results have shown that when the velocity difference associated with the peak shear is greater than \(\Delta V\), the shear segment is usually associated with data contaminated by ground clutter or point targets. Therefore, these shear segments are discarded.

b. Feature extraction

In active weather situations, it is not unusual for there to be 200 or more valid shear segments from a single elevation scan. Individual segments are combined into a common feature based on the spatial proximity (azimuthally and radially) of their peak-
vertical continuity box of a feature is obtained by drawing lines 5 km on either side of the line connecting the endpoints of the feature and then shifting the box until its centroid is aligned with the centroid of the feature (Fig. 3). Vertical continuity boxes are generated for features at both elevation scans. Vertical association can be established either by having the centroid of a feature at the upper scan fall within the box of a feature at the lower scan, or vice versa. When two or more features are vertically associated and one of the features is longer than 10 km, their shear segments are combined together to form a detected gust front.

There are, however, two situations in which single features, not meeting the above criteria, can be declared as detected fronts.

1) If a feature does not have vertical continuity, it is declared a front detection when it is longer than a specified length threshold (presently 15 km) and is the longest of those features not vertically associated. This allows for the detection of shallow gust fronts at distant ranges (only one per volume scan).

2) If there are no fronts detected within 10 km of the radar but a feature longer than the minimum front length threshold is detected at the upper scan within 10 km of the radar, it is added to the list of detected fronts. This helps the algorithm detect fronts in regions where the removal of ground clutter–contaminated data (section 4a) and beam blockage effects are significant at the lowest elevation scan.

d. Gust-front representation

To better accommodate the display and tracking of gust fronts, each detected front is represented by a high-order polynomial (Witt and Smith 1987). The peak shear locations from all vertically associated features of a particular front are used in estimating the polynomial coefficients. By application of a least-squares technique, a fifth-order polynomial,

$$y = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + b_5 x^5$$  \(1\)

is used to describe the gust-front location if the detection’s length is greater than 20 km. For aesthetic reasons, the algorithm uses a third-order polynomial to describe gust fronts with lengths less than or equal to 20 km. The subscripted constants in (1) are the polynomial coefficients, and \((x, y)\) are Cartesian coordinate pairs defined in a local coordinate system such that the line connecting the endpoints of the gust front is parallel to the \(x\) axis and the \(y\) axis passes through the centroid. Once the front has been described by the appropriate polynomial, its length is calculated as the pathlength between endpoints. Polynomial fitting provides a relatively smooth curve, which generally represents the true locations of peak shear well.

e. Wind-shear hazard

To estimate the wind-shear hazard that an aircraft penetrating a gust front might experience, the mean, plus one standard deviation, of the 1-km peak-shear values within the gust front is computed. Empirically, this value has been fairly representative of the shear experienced by pilots. The maximum of the peak shear values is not used since this value may be very unrepresentative if data preprocessing techniques fail.

f. Time association and forecasting of gust fronts

If one or more gust fronts are detected on two consecutive radar volume scans, an attempt is made to associate the detections in time. Time associations are made when the distance between the two front centroids is within a 10-km range threshold. This equates to a gust front propagation speed of 33.3 m s\(^{-1}\) for volume scan update rates of 5 min. The gust front centroid is an average value of all the peak-shear locations from the vertically associated features. If there is more than one association in time, the algorithm chooses the detection whose centroid is the closest.

Similar to the vertical association and time association techniques, the algorithm’s forecasting technique relies on centroids to determine the direction and speed of gust-front movement. After two detections are time associated, the gust front propagation vector is calculated by using the component of the centroid-to-centroid motion that is perpendicular to the line connecting the endpoints of the gust front from the current volume scan. This vector is used to translate, at a uniform speed and direction, the points of the current frontal position for each forecasting time interval. Previous attempts to use the entire propagation vector of
the centroid-to-centroid track to predict gust-front positions, rather than the normal component, often resulted in large forecast errors. These large errors usually occurred when the length of the detections changed significantly between volume scans, resulting in the gust fronts being forecasted to move long distances in directions almost parallel to their orientations.

g. Detection of fronts near and over the radar

As a gust front moves closer to the radar, the portion of the front having significant radial convergence (greater than a 5 m s\(^{-1}\) velocity difference across the frontal zone) decreases. For a front with a uniform velocity difference of 10 m s\(^{-1}\) and length of 50 km, the decrease in algorithm detection capability resulting from the changes in radar viewing angle is given in Fig. 4. For this simple representation, as the range from the radar to the gust front decreases from 15 to 5 km, the maximum detectable length (using a 5 m s\(^{-1}\) velocity difference criterion) decreases from 50 km to about 10 km. The detection of close-in gust fronts may be further degraded by nonuniform intensity, different orientations or curvatures, data artifacts produced by ground clutter, second-trip data removal, and beam blockage.

Although a technique to address this problem is not functional in the initial deployment of the TDWRs, it will be implemented in one of the first software upgrades. The objective of the “overhead-tracking” technique is to maintain the length and accuracy of gustfront detections as long-lived gust fronts pass near and over the radar.

Overhead tracking will initiate when the midpoint or either endpoint of a detection is within an adaptable range threshold (currently 20 km) and the detection is propagating toward the radar with a speed greater than 4 m s\(^{-1}\) (adaptable). In addition, the front must have been detected on the two previous volume scans.

Once overhead tracking is initiated for a front, the overhead-tracking front is checked for time association with regular GFDA detections from the next volume scan. In addition, a match is established only if the orientation difference between the fronts is less than 45°. If a match is found, the forecasted locations of the overhead-tracking front are examined to see which is nearest to the chosen GFDA detection (Fig. 5). The nearest forecast (1-min intervals) is then merged with the chosen GFDA detection. A final representation is obtained by smoothing this merger using a polynomial of the appropriate order (third or fifth).

If no time association between the overhead-tracking front and a detection from the next scan results, “coasting” is used to generate a detection. This detection is set to the 5-min forecast of the overhead-tracking front. A sequence of GFDA detections (Fig. 6) shows how detections are sustained and lengthened by this technique. The detections in Figs. 6a, 6f, 6g, 6h, and 6i show how the overhead-tracking technique maintains gust-front length as the front passes over the radar. The GFDA detections in Figs. 6b–e are examples of coasting.

The overhead-tracking process is aborted if the overhead-tracking front moves outside a specified range or if the propagation speed falls below 2 m s\(^{-1}\). Additionally, orientation checks, proximity checks, and coasting persistence thresholds may also cancel overhead tracking.
The wind-shear hazard estimates and the wind estimates for the overhead-tracking detection are set to those of the original GFDA detection if an original detection–forecast merger was used by the technique. If coasting is used, the wind-shear hazard estimates and wind estimates are set to those of the previous volume scan. If the overhead-tracked detection is generated entirely by coasting for more than three consecutive scans, the wind-shear hazard estimate is set to a missing status. Forecasts are generated for overhead-tracking detections in the same manner as other GFDA detections (section 2f).

3. The wind-shift algorithm (WSA)

The wind-shift algorithm was developed to estimate the mean wind speed and direction directly behind a gust front. Knowledge of the impending wind shift, using the GFDA’s forecasts and the WSA’s wind estimates, allows air traffic management to change runway configurations with minimal impact to aircraft traffic.

This algorithm was adapted from the Next Generation Weather Radar (NEXRAD) velocity–azimuth display algorithm (Browning and Wexler 1968), which uses a least-squares technique to estimate the wind vector from the radial velocity field. Initial testing of the WSA began during the 1987 TDWR experiment in Denver. Although this technique also provides a reasonable estimate of the mean wind ahead of the gust front, this is not required for the TDWR system, since other sensors directly measure winds at the airport.

Wind estimates are produced using radial velocity data in a sector behind the gust front. For each detected gust front, two spatial sectors are defined, from which the radial velocity data are selected (Fig. 7). The gust-front propagation vector is subsequently used to determine which data sector is behind the front.

For each gust-front data sector, two estimates of the horizontal wind are obtained. The first estimation technique assumes a uniform, horizontal wind field within the specified sector (uniform wind model). For this technique, a lower limit on the sector’s azimuthal width of 30° is used to reduce estimation error variance.
Smith and Rabin (1989) provide a detailed error analysis of the approach described in this section.

The second technique constrains the horizontal wind direction to be perpendicular to the gust-front orientation angle (perpendicular wind model). For fronts whose azimuthal extent is smaller than 30°, horizontal wind estimates are always obtained from the perpendicular wind model.

For the uniform wind model, the horizontal wind components \((u_0, v_0)\) and radial velocities \(v_r\) are related by

\[
v_r = u_0 \sin \theta \cos \phi + v_0 \cos \theta \cos \phi + \epsilon,
\]

where \(\theta\) is the azimuth angle from north, \(\phi\) is the radar elevation angle, and \(\epsilon\) is an unknown error owing to Doppler velocity measurement uncertainty and wind components not modeled by the first two terms of (2).

Estimates of the wind components \((u_0, v_0)\) are obtained by regressing the radial velocities within each sector onto the functions \(\sin \theta\) and \(\cos \theta\) and minimizing the sum of the squared errors, \(\epsilon^2\). The elevation dependence in (2) is neglected because, for the elevation angles considered here, \(\cos \phi \sim 1\). Details of the linear regression can be found in Smith (1986).

For the perpendicular wind model, the Doppler velocity \(v_r\) and the horizontal wind speed \(|V|\) are related by

\[
v_r = |V| \cos \psi + \epsilon,
\]

where the angle \(\psi\) is the difference between the radar azimuth and the angle perpendicular to the gust-front orientation. Using linear regression techniques, the estimate of the wind speed behind the gust front, \(|\hat{V}|\), is given by

\[
|\hat{V}| = \frac{\sum_{i=1}^{N} v_{ri} \cos \psi_i}{\sum_{i=1}^{N} \cos^2 \psi_i},
\]
with the summations performed for all \( N \) data points within the specified spatial sector. Hence, the wind-speed estimate is a weighted average, in a least-squares sense, of the wind component perpendicular to the front.

For both techniques, after the initial least-squares fit of the radial velocity data, individual points are rejected if they are not within twice the root-mean-square error (rmse) about the fit. After an initial pass at removing outliers, the procedure is repeated. This two-pass fit is designed to reject data anomalies that might negatively affect the quality of the horizontal wind estimates. The rmse value, in addition to its use for outlier rejection, is also used to determine wind estimate quality. If after the second fit, the rmse is larger than 3 m s\(^{-1}\), the wind estimate is rejected.

Gust-front tracking and orientation information are used to determine which side of the gust front is the outflow side (behind) and also for quality control of the horizontal wind estimates. On occasion, significant nonuniformities in the wind field behind gust fronts, and/or data preprocessing errors, may occur and cause erroneous wind estimates. Thus, a wind estimate is rejected if the difference between the wind-direction estimate and the gust-front orientation is less than an adaptable threshold of 25° (i.e., wind direction nearly parallel to gust-front orientation). Wind-direction estimates for both long and short (azimuthal extent less than 30°) gust fronts are also checked against the gust-front propagation direction. Estimates with a component opposite the propagation direction are rejected, as are estimates with extreme magnitudes (>40 m s\(^{-1}\)).

For the spatially averaged estimates that the algorithm produces, wind estimates greater than 40 m s\(^{-1}\) have been associated with errors in data preprocessing (residual range-obscured data or velocity dealiasing errors within the data sector). Wind estimates obtained using the uniform wind model that fail any of these validity checks are replaced with the perpendicular wind model estimate. Since perpendicular wind model estimates are also constrained by these validity checks, occasionally no wind estimate is produced by the WSA. A comparison of the estimates from the two techniques and surface-based mesonet measurements was completed in 1988 prior to finalizing this series of validity checks (Witt et al. 1989).

4. Performance evaluation of the GFDA and WSA

The purpose of a performance evaluation is to assess the ability of the algorithm to deliver reliable and accurate products. The TDWR GFDA and WSA provide the following products related to gust-front detection and prediction: current locations, forecasted locations, wind speed and direction behind the gust fronts, and the wind-shear hazard to arriving and departing aircraft. The algorithm products were obtained by processing the TDWR test-bed radar data using the suggested values for the adaptable thresholds mentioned in section 2.

Data were collected near Denver, Colorado; Kansas City, Missouri; and Orlando, Florida, during June–August 1988, March–August 1989, and June–August 1990, respectively. The gust fronts in the database resulted from thunderstorms that developed in a broad spectrum of synoptic and mesoscale situations. Thus, the results should be applicable to the full range of United States TDWR locations.

Prior to algorithm invocation in the TDWR test-bed, efforts were made to address various data artifacts that are frequently observed in the data of weather radars. The test-bed data were preprocessed using techniques functionally similar to those to be used in the TDWR systems.

(a) Data preprocessing

The data used for most algorithm development and subsequent performance evaluation were collected by the TDWR test-bed radar, developed and operated for the FAA by the Massachusetts Institute of Technology Lincoln Laboratory. Most data were collected at S band with a 1.0° beamwidth (Evans and Johnson 1984). After 1990, this radar operated at C band with a beamwidth of 0.5° (Bernella 1991). Because velocity aliasing range obscuration by out-of-trip weather echoes and ground clutter–contaminated velocities can adversely affect algorithm performance, the GFDA and WSA need as input good quality Doppler radar data.

To alleviate the problem of velocity aliases, a local environment dealiasing scheme was implemented to automatically edit and dealias the radial velocity data. Editing and dealiasing are accomplished by a series of comparisons of a velocity in question with neighboring values, both along the same radial and in an adjacent radial. Within this two-dimensional approach, there are a number of validity checks designed to prevent errors from occurring or, if they do, prevent them from propagating. This approach is superior to one-dimensional techniques, which utilize single radials of velocities. A detailed description of this dealiasing technique can be found in Eilts and Smith (1989). Although the performance statistics presented in this paper used the aforementioned velocity dealiasing technique, another algorithm (Wieler 1991; Sykes and Stevens 1991), which also uses a two-dimensional approach, will be used in the TDWR system.

Spatial variations in ground clutter can introduce regions of spurious Doppler velocity. When ambient flow near the radar encounters ground clutter having a near-zero velocity, an apparent radial convergence zone is created and false gust-front detections may result. To prevent these false detections, it is necessary to suppress ground clutter contamination as much as possible. To this end, the TDWR radar has an advanced ground clutter suppression system. It initially passes
incoming data through high-pass digital filters (Evans 1983), which remove most of the data contamination caused by ground clutter close to the radar. A clutter residue map flags the remaining clutter-contaminated areas (Mann 1988). A detailed description of the ground clutter suppression methods used in the TDWR system is given in Wieler and Shrader (1991).

Contamination of first-trip data by out-of-first-trip weather signals, commonly called range obscuration, can also result in false gust-front detections. To minimize the effects of range obscuration, two methods are used (Rhoda and Stevens 1991). The primary method uses adaptive pulse repetition frequency (PRF) selection (Crocker 1988) to attempt to minimize the obscurace in specific regions of interest (near-airport environment). The secondary method, range obscurace editing, attempts to flag first-trip sample volumes that are significantly contaminated.

Collectively, these data preprocessing techniques assure high quality data for the GFDA and WSA to process. These and other limitations of pulsed-Doppler radar observations of the atmosphere are discussed further in Doviak and Zrnić (1984).

b. Gust-front detection

One output of the GFDA is a curve or “detection” representing the current location of the gust front. Verification of the GFDA detections is based upon automatically comparing these detections to “ground truth” generated by meteorologists using single-Doppler reflectivity and velocity data (Klinge-Wilson et al. 1992). Ground truth is generated for every volume scan (5-min interval) of the database, and thus, a single gust front produces numerous “events.”

The ground truth is represented by a box, 5 km wide, centered on and extending along the length of the gust front. A box width of 5 km is used to compensate for location errors introduced during the ground-truthing process. Ground truth is also categorized by gust-front strength (Table 1). Strength estimates are determined subjectively from the 0.5° radial velocity fields by estimating a mean radial velocity on both sides of the gust front and computing an absolute difference.

The probability that a portion of a gust front, represented by the ground-truth box, is detected by the GFDA is given by the probability of local detection (PLD). PLD for a given radar volume scan is the length of the ground-truth boxes that are overlapped by detections, divided by the total length of the ground-truth boxes. Figure 8 provides an example of an event where the PLD is about 0.6.

Table 2 summarizes the PLD of the GFDA as a function of locale and gust-front strength. The best detection performance is associated with severe Denver events. Overall, the GFDA detects gust fronts best in Kansas City and when gust fronts are severe. For all events (regardless of location and strength), the PLD is 0.41. If one assumes that the only operationally significant gust fronts are moderate or greater in strength, then the weak events can be ignored. For events that are moderate or greater in intensity, the PLD is 0.49. Of the 2021 events represented in the data, the GFDA detected some part of 64.3% of all events, and 81.7% of all fronts moderate or greater in strength (not shown in the tables).

Since the GFDA may produce false detections that are not associated with any wind shear or wind shift in a particular location (e.g., due to errant data preprocessing and vertical wind shear), a second measure is necessary to quantify performance. The probability of false detection (PFD) is the probability that a portion of a detection (or the entire detection) does not overlap the ground-truth box. For a given volume scan, PFD is equal to the length of detections outside ground-truth boxes divided by the total length of detections. For the example in Fig. 8, the PFD is about 0.25.

The PFD of the GFDA is summarized in Table 3. The composite PFD is 0.16. The highest PFD is observed with the Kansas City portion of the database. Of the 199 entirely false detections considered in this assessment, 180 of them occurred in Kansas City. Analysis of all the false detections indicated that many were due to data quality problems (31% from range-folded returns, 19% from improperly dealiased velocities, and 5% from ground clutter breakthrough). Many false detections (37%) were also due to vertical shear of the horizontal wind field not related to gust fronts.

<table>
<thead>
<tr>
<th>Category</th>
<th>Mean radial velocity difference</th>
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<tbody>
<tr>
<td>Weak</td>
<td>≥5 m s⁻¹ and &lt;10 m s⁻¹</td>
</tr>
<tr>
<td>Moderate</td>
<td>≥10 m s⁻¹ and &lt;15 m s⁻¹</td>
</tr>
<tr>
<td>Strong</td>
<td>≥15 m s⁻¹ and &lt;25 m s⁻¹</td>
</tr>
<tr>
<td>Severe</td>
<td>≥25 m s⁻¹</td>
</tr>
</tbody>
</table>

Fig. 8. Example of a GFDA detection and a ground-truth location from the performance evaluation database. The ground truth is represented by the box, and the solid line is the detection.
TABLE 2. Probability of local detection by the GFDA (kilometers of GFDA detections divided by kilometers of ground truth).

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Weak</td>
<td>639/18 986 = 0.34</td>
<td>2354/4935 = 0.48</td>
<td>2118/9938 = 0.22</td>
<td>10 869/33 859 = 0.32</td>
</tr>
<tr>
<td>Moderate</td>
<td>6495/12 907 = 0.51</td>
<td>2991/5876 = 0.51</td>
<td>3354/8380 = 0.40</td>
<td>12 840/27 163 = 0.47</td>
</tr>
<tr>
<td>Strong</td>
<td>2875/4648 = 0.62</td>
<td>3384/6397 = 0.53</td>
<td>1034/2469 = 0.42</td>
<td>7293/13 514 = 0.54</td>
</tr>
<tr>
<td>Severe</td>
<td>32/32 = 1.00</td>
<td>652/932 = 0.70</td>
<td>50/126 = 0.39</td>
<td>734/1090 = 0.67</td>
</tr>
<tr>
<td>All</td>
<td>15 799/36 573 = 0.43</td>
<td>9381/18 140 = 0.52</td>
<td>6556/20 913 = 0.31</td>
<td>31 736/75 626 = 0.42</td>
</tr>
</tbody>
</table>

with low-level jets accounting for 6%. The remaining 8% of the false detections resulted from various sources (e.g., data contaminated by point targets, sidelobe returns). Additional discussion of false detections produced by vertical wind shear is presented in section 4c.

c. Overhead tracking

Testing of the overhead-tracking technique was accomplished using data collected in Denver (1988) and Kansas City (1989). Datasets with known false detections caused by low-level jets, typically occurring within the overhead-tracking range, were purposely included in the database. A total of 203 scans with fronts passing over or near the radar were processed. The GFDA, using overhead tracking, detected 176 of the 203 events (87%). Without overhead tracking, the GFDA detected 142 of the 203 events (70%). Because the overhead-tracking technique assumes steady-state motion, false detections may be created when the gust-front propagation speed rapidly increases or decreases over the period of a volume scan. For the 203 scans used for evaluation, the GFDA without overhead tracking produced 18 false alarms. The GFDA with overhead tracking produced 24 false alarms. Thus, a false-alarm ratio [FAR, the number of false detections divided by the number of total detections (Donaldson et al. 1975)] of 12% was maintained in both cases. Implementation of an improved forecasting technique (Hermes et al. 1990), which does not rely on centroid locations to produce the propagation vector, will likely reduce the number of false alarms produced by overhead tracking.

d. Gust-front forecasting

For gust fronts that impact an airport, it is important to assess if air traffic management received sufficient notification of the impending wind shift from the TDWR. To properly evaluate the GFDA forecast function, it is necessary to know how well gust fronts are forecasted and how well those forecasts verify. For the verification of GFDA forecasts, 10- and 20-min forecasts of future gust-front locations were compared to both ground-truth boxes and GFDA detections at the validation times.

The appropriate performance metrics for evaluating the forecast function are the probability of generating a forecast (PF), the correct forecast probability (CFP), and the false forecast probability (FFP). There are two methods for computing PF. The first is the number of forecasts divided by the number of valid detections (PF|d). The algorithm can generate forecasts only after it has detected the event; PF|d gives the probability of generating a forecast given the detection of gust fronts on two consecutive volume scans. This measure is useful for showing the potential of the forecasting technique, as it removes from the database those events not detected by the algorithm. The second technique is the number of forecasts divided by the number of events (PF|e). This metric is important to the user who wants to know the probability of generating a forecast for a gust front that impacts the airport, regardless of whether or not the gust front was detected by the GFDA. Similar to the PLD metric of the detection evaluation, CFP, for a given volume scan, is the length of the ground-truth boxes that are overlapped by forecasts divided by the total length of the ground-truth boxes. The FFP metric is equal to the length of forecasts outside the ground-truth boxes divided by the total length of the forecasts (similar to PFD of section 4b). The PF|e and PF|d for GFDA forecasts, as a function of location, are given in Table 4. The highest probability of generating a forecast, given either a detection or an event, is associated with Kansas City data (1989). The lowest probability of generating a forecast is associated with Orlando data (1990). For all locations, the overall probability of generating a forecast for any event is 0.45; this result shows the combined limitations of the algorithm detection and forecasting.

TABLE 3. Probability of false detection by the GFDA (kilometers of GFDA detection divided by kilometers of ground truth).

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PFD</td>
<td>968/16 792 = 0.06</td>
<td>4743/14 668 = 0.32</td>
<td>336/6899 = 0.05</td>
<td>6047/38 359 = 0.16</td>
</tr>
</tbody>
</table>
Table 4. Probability of generating a forecast.

<table>
<thead>
<tr>
<th></th>
<th>PF/e</th>
<th>PF/d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denver (1988)</td>
<td>449/1013 = 0.44</td>
<td>449/654 = 0.69</td>
</tr>
<tr>
<td>Kansas City (1989)</td>
<td>279/503 = 0.55</td>
<td>279/374 = 0.75</td>
</tr>
<tr>
<td>Orlando (1990)</td>
<td>180/505 = 0.36</td>
<td>180/272 = 0.66</td>
</tr>
<tr>
<td>Composite</td>
<td>908/2021 = 0.45</td>
<td>908/1300 = 0.70</td>
</tr>
</tbody>
</table>

techniques. When the performance of the forecasting technique is isolated, the probability of generating a forecast for a detected event is 0.70.

CFP, as a function of event strength and location, for 10- and 20-min forecasts is given in Tables 5 and 6, respectively. FFP, as a function of location, for 10- and 20-min forecasts is given in Table 7. For 10-min forecasts, the probability of forecasting the portion of the event that impacts a specific airport location (for all strengths and locations) to within ±2.5 km is 0.20, and the probability that a forecast will not verify is 0.39. The best forecasting performance (CFP) is associated with Denver (1988) events, while FFP is greatest for Kansas City events.

Forecasts are generated by moving the detection based upon the estimated propagation speed and desired forecast interval. This technique does not allow for changes in the shape and orientation of the gust front or the dissipation of the gust front. For the latter, a forecast is considered a false forecast if it is made for a gust front that dissipates before the forecast validation time. An example of the impact of gust-front orientation change on forecast performance is illustrated in Fig. 9, which shows a detection, 10-min forecast and ground truth. In Fig. 9a, the ground truth is used for evaluating the detection, while in Fig. 9b the ground truth is used for evaluating the forecast. In this case, the gust front was forecasted to propagate due north with an east–west orientation. However, the shape and orientation of the gust front changed over the 10-min period, resulting in a CFP of about 0.40 and an FFP of about 0.65.

Surveys pertaining to the usefulness of the various TDWR products were given to air traffic controllers and supervisors following test-bed operations from 1988 to 1991. Pertaining to the GFDA products, the controllers and air traffic supervisors were asked to rate: 1) the usefulness of the gust-front detection, and 2) the usefulness of the wind-shift prediction. The possible ratings were +3—very good, +2—good, +1—fairly good, 0—fair, -1—fairly poor, -2—poor, -3—very poor, and ?—do not know. The ratings for the 4-yr period are summarized in Tables 8 and 9. For this period, 90% of the air traffic controllers rated the usefulness of the GFDA gust-front detections with a value greater than +1 (fairly good). Eighty-five percent of the air traffic controllers rated the usefulness of the GFDA wind-shift prediction products with a value greater than +1.

Operationally, the forecasts serve as a “heads up” warning to the air traffic control (ATC) supervisors. The forecast information is used to coordinate the potential runway configuration changes with the various air traffic managers, but typically, runways are not reconfigured until the wind shift is confirmed [e.g., by a wind change at an outlying Low-Level Wind Shear Alert System (LLWAS) anemometer]. Thus, the forecast information helps to reduce delays associated with runway reconfigurations by allowing traffic managers to plan for, rather than react to, gust-frontal passages.

Errors in the shape of the gust front and/or positional location errors at a fixed prediction time are not as important to the ATC users as the fact that a gust front or wind shift is approaching. Although the FFP in Fig. 9 is about 0.65, the ATC user would probably consider this to be a good forecast. Thus, the quantitative results from the automated scoring procedure do not necessarily represent the operational usefulness of the product. Rather, the scoring methodology provides a baseline against which future enhancements to the algorithm can be evaluated easily.

The remaining metric used to evaluate GFDA forecasts utilizes the GFDA detections at +10 and +20 min as the verification location of an event. The distances between the GFDA forecasts and the +10 and +20 min detections, along the entire length of the forecast, were calculated and then averaged to give a measure of the location error. The distribution of the location errors for the 10- and 20-min forecasts are shown in Figs. 10 and 11, respectively. The results of this analysis are summarized in Table 10. The average magnitude of the distance between the 10-min forecasts and the corresponding detections was 2.3 km, while for 20-min forecasts it was 3.6 km.

Table 5. Probability of correct 10-min forecasts at a location along the gust front (kilometers of GFDA detection divided by kilometers of ground truth).

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Weak</td>
<td>2805/17 932 = 0.16</td>
<td>437/4489 = 0.10</td>
<td>981/9887 = 0.10</td>
<td>4223/32 308 = 0.13</td>
</tr>
<tr>
<td>Moderate</td>
<td>3215/12 178 = 0.26</td>
<td>1022/5404 = 0.19</td>
<td>2273/8578 = 0.26</td>
<td>6510/26 160 = 0.25</td>
</tr>
<tr>
<td>Strong</td>
<td>1150/4497 = 0.26</td>
<td>1680/5680 = 0.30</td>
<td>546/2396 = 0.23</td>
<td>3376/12 573 = 0.27</td>
</tr>
<tr>
<td>Severe</td>
<td>0/32 = 0.0</td>
<td>324/998 = 0.32</td>
<td>79/126 = 0.63</td>
<td>403/1156 = 0.35</td>
</tr>
<tr>
<td>All</td>
<td>7170/34 639 = 0.21</td>
<td>3463/16 571 = 0.21</td>
<td>3879/20 987 = 0.18</td>
<td>14 512/72 197 = 0.20</td>
</tr>
</tbody>
</table>

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Table 6. Probability of correct 20-min forecasts at a location along the gust front (kilometers of GFDA detection divided by kilometers of ground truth).

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Weak</td>
<td>2014/17 745 = 0.11</td>
<td>181/4265 = 0.04</td>
<td>818/9979 = 0.08</td>
<td>3013/31 989 = 0.09</td>
</tr>
<tr>
<td>Moderate</td>
<td>1898/12 542 = 0.15</td>
<td>625/5254 = 0.12</td>
<td>1542/8407 = 0.18</td>
<td>4065/26 203 = 0.16</td>
</tr>
<tr>
<td>Strong</td>
<td>667/4345 = 0.15</td>
<td>1134/5641 = 0.20</td>
<td>251/2396 = 0.10</td>
<td>2052/12 382 = 0.17</td>
</tr>
<tr>
<td>Severe</td>
<td>0/32 = 0.0</td>
<td>123/966 = 0.13</td>
<td>45/126 = 0.36</td>
<td>168/1124 = 0.15</td>
</tr>
<tr>
<td>All</td>
<td>4579/34 664 = 0.13</td>
<td>2063/16 126 = 0.13</td>
<td>2656/20 908 = 0.13</td>
<td>9298/71 698 = 0.13</td>
</tr>
</tbody>
</table>

Overall, there was a general tendency for the Kansas City forecasts to be less accurate than those in Denver or Orlando (see Tables 5, 6, 7, and 10). One possible explanation for this is that the gust fronts in Kansas City tended to have higher propagation speeds than those in Denver or Orlando. Since the propagation speed and direction used for forecasting are based upon the detection centroids from consecutive volume scans, significant changes in the radar viewing angle of a fast-moving front would likely degrade the forecast accuracy.

e. False GFDA detections caused by vertical wind shear

In the performance evaluation in section 4b, vertical wind shears were responsible for many false detections by the GFDA. Classification of vertical wind-shear events as gust fronts is misleading, since a sustained wind shift at the surface does not necessarily result. In addition, the hazard warning from the GFDA algorithm is always a gain estimate. From a safety viewpoint, this warning would be inappropriate, since performance gains or losses may occur as the aircraft passes through a level of strong vertical wind shear.

Of these vertical wind-shear events, about 20% were associated with a low-level jet (LLJ) occurrence. During a low-level jet event, strong low-level winds are decoupled from the stable surface layer resulting in strong vertical shear of the horizontal wind in the lowest 2 km of the troposphere. The low-level jet typically occurs during the night and is prevalent from the southerly direction in spring in the Great Plains (Bonne 1968).

When a radar beam points in the direction of the approaching jet core, the vertical shear of the horizontal wind across the LLJ–stable layer interface manifests itself as radial convergence in the Doppler velocity data. As a result, a study was conducted to determine whether adjustments to algorithm site-adaptable parameters could eliminate these false detections. Figures 12 and 13 show the distributions of the average peak shear and average velocity difference, respectively, for the 17 LLJ and 41 gust-front detections. These averages are determined from all the shear segments that make up the detection. The distribution of these data clearly show that simply increasing either of these site-adaptable parameters would seriously impact detection performance. Other site-adaptable parameters were also varied, but those modifications had little impact on reducing the number of LLJ-induced detections.

The false detections produced by vertical wind shear are an additional concern because they occurred at distances comparable to the typical TDWR-to-airport distance. This results in an increase in false alarms at the airport. Some mitigation of vertical wind shear false alarms near airports may occur at locales where radar siting happens to be favorable. However, a more aggressive approach, possibly using the TDWR to detect the vertical wind shear associated with the LLJ, may be necessary to distinguish this phenomenon and eliminate these false detections.

While it is important to eliminate false GFDA detections caused by vertical wind shear, the hazard of vertical wind shear to aviation should not be ignored. A 10-yr summary (1978–1987) of wind-shear-related general aviation accidents (most occurring during landing or takeoff procedures) showed that 52.3% were associated with some type of vertical wind shear, with 4.5% specifically identified as being associated with the LLJ (S. Oakland-Cobb 1991, personal communication). The potential aircraft hazard of a particular LLJ event is discussed by Hermes et al. (1990).

f. Wind-shear hazard

The GFDA wind-shear hazard estimates were evaluated by comparing them to pilot reports (PIREPS)

Table 7. Ten- and twenty-minute false forecast probability.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10-min FFP</td>
<td>4393/11 620 = 0.38</td>
<td>4068/7708 = 0.53</td>
<td>1068/4822 = 0.22</td>
<td>9529/24 150 = 0.39</td>
</tr>
<tr>
<td>20-min FFP</td>
<td>6887/11 590 = 0.59</td>
<td>4916/7133 = 0.69</td>
<td>1721/4501 = 0.38</td>
<td>13 524/23 224 = 0.58</td>
</tr>
</tbody>
</table>
of wind shear recorded by ATC observers at Denver in 1988. Twenty-nine PIREPS were available for the comparison. The average absolute difference between the PIREPS and the GFDA wind-shear hazard estimate was about 10 kt (~5 m s⁻¹), with the GFDA typically overestimating the wind-shear hazard relative to the PIREPS (Kingle-Wilson et al. 1989).

The simple model that describes an aircraft encounter with a gust front indicates that the aircraft should always experience a gain in wind speed. As the airplane flies into the gust front, it encounters an increasing head wind. As the plane flies out of a gust front, it experiences a decreasing tail wind. Both flight paths result in a performance gain. Therefore, the wind change associated with GFDA detections is always reported as a gain. Among the PIREPS in the comparison database were reports of aircraft performance losses. If these reports are removed from the comparison, the average absolute difference between the PIREPS and GFDA hazard estimates is reduced to about 5 kt. Cases in which pilots reported a loss need to be studied further to determine why there was an inconsistency between the PIREPS and the GFDA hazard warnings.

g. Horizontal wind estimate

The WSA estimates the speed and direction of the wind behind the gust front. [Direct measurements of

The wind ahead of the gust front is provided by LLWAS (Goff 1980).] As part of the TDWR concept validation effort in Denver, Kansas City, and Orlando, a network of 30–40 automated weather observing stations (Wolfson 1989) was located around the various airports. The observations of horizontal surface winds obtained by the mesonet stations provide an independent data source for validating the algorithm wind estimates.

The TDWR test-bed radar was typically located about 15 km from the airport it covered. For reasons discussed in section 2g, the GFDA had difficulty detecting gust fronts close to the radar and, therefore, over the mesonet. This was particularly true in Kansas City and Orlando. Evaluation of the WSA wind estimate was difficult because there were few observations generated while the gust front was over the mesonet. To increase the sample size, WSA estimates made within 10 min of the time the wind shift was observed in the mesonet were included in the assessment. Since the WSA estimates are intended to be representative of the mean wind behind the gust front and are used in a predictive manner, including these data in the analysis should not invalidate the results. Nine of the algorithm observations during 1990 were obtained in this way.

The mesonet data used to assess the accuracy of the wind-shift estimate were the wind speed and direction averaged over 1 min, and the peak wind speed that

TABLE 8. Usefulness of the gust-front detections.

<table>
<thead>
<tr>
<th>Rating scale</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988 (Denver)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1989 (Kansas City)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>1990 (Orlando)</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>12</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>1991 (Orlando)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>4-yr overall</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>11</td>
<td>20</td>
<td>52</td>
<td>2</td>
</tr>
</tbody>
</table>

TABLE 9. Usefulness of the wind-shift predictions.

<table>
<thead>
<tr>
<th>Rating scale</th>
<th>-3</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988 (Denver)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>1989 (Kansas City)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>1990 (Orlando)</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>12</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>1991 (Orlando)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>4-yr overall</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>9</td>
<td>25</td>
<td>42</td>
<td>3</td>
</tr>
</tbody>
</table>
occurred during the 1-min period. As gust fronts passed through the network, the stations that experienced the wind shift were identified. The 1-min averages and peak wind speeds were averaged over these stations to produce averaged 1-min direction, averaged 1-min speed, averaged peak speed, and overall peak speed. These values were then compared to the WSA estimates. The results are compiled in Table 11. On average, the algorithm-generated wind directions were within 24° of the mesonet average direction. Overall, the algorithm-generated wind speeds agree most closely with the averaged peak speed (mean absolute difference of 2.3 m s⁻¹). Since the algorithm processes data collected over a region that is spatially larger than, but on time scales shorter than, the ground-based network, areal averaging (over all stations) of the peak wind speed provides the best match between the spatial and temporal scales of the two measurement systems. In addition, the radar samples the wind field from 40 to 140 m above the ground-based sensors, which may account for some of the observed differences.

5. Algorithm limitations

In addition to the performance evaluation provided in this paper, real-time and postanalysis testing and evaluation of the GFDA and WSA have occurred since 1987. Based on this experience, deficiencies in several techniques used by the TDWR gust-front detection algorithm have been discovered and are discussed in further detail in Hermes et al. (1990).

One potential weakness of the algorithm is the vertical continuity technique. Currently, vertical conti-

![Fig. 10. Forecast location error (km) for the 10-min GFDA forecasts. The 10-min forecast is compared to the location of the detection at the time that the forecast is valid.

![Fig. 11. Same as Fig. 10 except for 20-min GFDA forecasts.

### TABLE 10. Summary of the 10- and 20-min forecast location error.

<table>
<thead>
<tr>
<th></th>
<th>1988</th>
<th>1989</th>
<th>1990</th>
<th>Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10-min</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forecasts/verification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of cases</td>
<td>307</td>
<td>143</td>
<td>74</td>
<td>524</td>
</tr>
<tr>
<td>Mean of average distance (km)</td>
<td>2.0</td>
<td>3.5</td>
<td>1.4</td>
<td>2.3</td>
</tr>
<tr>
<td>Standard deviation of average distance (km)</td>
<td>1.9</td>
<td>3.8</td>
<td>1.8</td>
<td>2.7</td>
</tr>
<tr>
<td><strong>20-min</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forecasts/verification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of cases</td>
<td>210</td>
<td>89</td>
<td>46</td>
<td>345</td>
</tr>
<tr>
<td>Mean of average distance (km)</td>
<td>3.2</td>
<td>5.6</td>
<td>1.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Standard deviation of average distance (km)</td>
<td>3.0</td>
<td>5.3</td>
<td>2.1</td>
<td>3.8</td>
</tr>
</tbody>
</table>
nuity is established by determining if feature centroids from the upper and lower scans fall within a vertical continuity box (section 2c). When features are highly curved, their centroids may not accurately represent the location of the feature and thus may not fall within this vertical continuity box. As a result, vertical continuity may not be established and the gust front may not be detected. Additionally, for gust fronts at longer ranges (>60 km), vertical continuity may not be established for shallow gust fronts where the upper elevation scan overshoots the phenomena.

Time association and forecasting also are based on centroid location (section 2f). Centroid location is dependent on the length and shape of a detection. If the detection length and/or shape changes dramatically with time, the centroid location may indicate a motion that is significantly different from the actual gust-front propagation vector. Preliminary assessment of an alternative technique, which uses the entire detection to determine the propagation vector, showed a reduction in 10-min forecast location error of 0.5 km on average (Hermes et al. 1990).

On occasion, the polynomial representation of the gust front does not match well the locations of the peak shear. This problem has been observed with merging outflows, outflows exhibiting multiple surges, and other complex wind regimes. For example, convergent features on both sides of the downdraft of radially expanding microbursts (near and far range) may be vertically associated. Since locations of the peak shears in these features are represented by $x$, $y$ coordinates (section 2d), there is a wide range of $y$ values for a given $x$ value. Therefore, a single polynomial cannot properly represent these regions.

Most of these problems occur infrequently and are short-lived when they do occur. Collectively, they degrade the accuracy and reliability of the GFDA and WSA. Plans to implement new or improved techniques are under way.

6. Summary and future plans

Significant improvements have been made in the functionality of the original gust-front algorithm developed by Uyeda and Zrnić (1986) and in providing
an operationally useful estimate of the wind shift occurring after the passage of a gust front. Preprocessing of the Doppler radar data to correct or remove bad data from velocity aliasing, ground clutter contamination, and range obscuration has also had a positive impact on algorithm performance. Together, these improvements have resulted in algorithms that operate reliably as part of the TDWR system.

Implementation of 1) velocity difference thresholding, 2) connection of nearby features into single features, 3) vertical association requirements, 4) third- and fifth-order polynomial fits in Cartesian coordinates, and 5) the use of normal components for tracking and forecasting have improved algorithm performance. The addition of a technique to estimate wind-shear hazard, and implementation of the WSA, produce the additional information required to complete the wind-shear hazard warning and wind-shift prediction functions of the GFDA.

The evaluation of the GFDA and WSA scheduled for initial deployment in the TDWR system showed operationally useful performance in tests at a number of representative locations. Improvements in detecting the full extent of a gust front, removal of false detections produced by vertical wind shear and data contamination, and forecasting improvements are still necessary.

Planned improvements include the addition of the overhead-tracking technique (section 2g; scheduled for an early operational TDWR system software upgrade) and use of azimuthal shear and reflectivity thin lines to improve detections (Klinge-Wilson 1991). Other approaches to vertical association, gust-front representation, and forecasting techniques have also been investigated (Hermes et al. 1990). A preliminary version of an algorithm that incorporates these changes is discussed by Eilts et al. (1991), and a preliminary performance assessment is presented by Klinge-Wilson et al. (1992). Although several improvements to the GFDA and WSA are needed and planned, the GFDA and WSA currently provide operationally useful information on both the hazardous wind shears and sustained wind shifts associated with gust fronts.

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