ABSTRACT

Storm identification, tracking, and forecasting make up an essential part of weather radar and severe weather surveillance operations. Existing nowcasting algorithms using radar data can be generally classified into two categories: centroid and cross-correlation tracking. Thunderstorm Identification, Tracking, and Nowcasting (TITAN) is a widely used centroid-type nowcasting algorithm based on this paradigm. The TITAN algorithm can effectively identify, track, and forecast individual convective storm cells, but TITAN tends to provide incorrect identification, tracking, and forecasting in cases where there are dense cells whose shape changes rapidly or where clusters of storm cells occur frequently. Aiming to improve the performance of TITAN in such scenarios, an enhanced TITAN (ETITAN) algorithm is presented. The ETITAN algorithm provides enhancements to the original TITAN algorithm in three aspects. First, in order to handle the false merger problem when two storm cells are adjacent, and to isolate individual storm cells from a cluster of storms, ETITAN uses a multithreshold identification method based on mathematical morphology. Second, in the tracking phase, ETITAN proposes a dynamic constraint-based combinatorial optimization method to track storms. Finally, ETITAN uses the motion vector field calculated by the cross-correlation method to forecast the position of the individual isolated storm cells. Thus, ETITAN combines aspects of the two general classes of nowcasting algorithms, that is, cross-correlation and centroid-type methods, to improve nowcasting performance. Results of experiments presented in this paper show the performance improvements of the ETITAN algorithm.

1. Introduction

Storm identification, tracking, and forecasting using radar data are important facets of forecasting the location and strength of severe weather events. Detecting storms, calculating their properties [such as centroid position, vertically integrated liquid water (VIL), volume, top height, etc.], and tracking and forecasting the evolution and movement of the storms make up an essential part of severe weather warning operations. These results can also serve as input to other radar-based severe weather detection algorithms, such as hail detection algorithms (Joe et al. 2004; Wilson et al. 2004). In addition to providing useful short-term forecasting, or nowcasting, capabilities, storm identification, tracking, and forecasting algorithms can also provide storm data suitable for the study of the physical mechanisms of storm evolution (Dixon and Wiener 1993).

Many nowcasting algorithms using radar data have been developed over the past decades. These algorithms
can be classified into two categories: cross-correlation tracking (Rinehart and Garvey 1978; Tuttle and Foote 1990; Li et al. 1995; Lai 1999) and centroid tracking (Bjerkaas and Forsyth 1979; Crane 1979; Austin and Bellon 1982; Rosenfeld 1987; Dixon and Wiener 1993; Johnson et al. 1998; Handwerker 2002). An excellent review of these methods is given by Wilson et al. (1998, 2004). Keenan et al. (2003) present an overview and comparison of nine existing nowcasting systems deployed in the forecast demonstration project during the 2000 Olympic Games in Sydney, Australia. Wilson et al. (2004) imply that the best approach to nowcasting is a hybrid approach. The National Center for Atmospheric Research’s (NCAR) AutoNowcasting (ANC) System (Mueller et al. 2003) is just such a data fusion system that utilizes fuzzy logic to combine various predictor fields to produce 0–1-h convective nowcasts. Lakshmanan et al. (2003) propose a novel hybrid technique that correlates the current storm shape backward with the previous radar image. This method is limited to two dimensions, focusing only on the tracking and forecasting and not on identification or attribute determination.

The cross-correlation method uses the 2D reflectivity data to calculate the motion vector field that can be used to forecast the storm movement. An example of this method is the Tracking Radar Echoes by Correlation (TREC) algorithm (Rinehart and Garvey 1979). The strength of the cross-correlation method is to provide more accurate speed and direction information of reflectivity echoes (Johnson et al. 1998). The correlation method can be used for both convective and stratiform precipitation events. The weakness is that it is unable to identify and track individual storms. The correlation method has been used in many nowcasting systems, such as ANC, the Integrated Terminal Weather System (ITWS) developed by the Massachusetts Institute of Technology–Lincoln Laboratory (MIT-LL) (Evans and Ducot 1994), and the Nowcasting and Initialization of Modeling Using Regional Observation Data System (Nimrod) developed by the Met Office (Golding 1998). Wolfson et al. (1999) proposes a Growth and Decay Storm Tracker, which is also based on the correlation method. The cross-correlation method is not only limited to tracking reflectivity fields as is stated. MIT-LL believes tracking VIL for convective cases to be more beneficial than tracking reflectivity.

The centroid-type methods first identify individual isolated storm cells within single radar volume scan data and try to match storms across consecutive scans followed by forecasting the storm position based on the identified storm centroid. The strength of the centroid-type method is that it tracks individual isolated storm cells effectively and can provide the temporal property data of storms (Johnson et al. 1998). Because centroid trackers depend upon thresholding techniques to distinguish individual convective storms, this makes them inappropriate for the nowcasting of stratiform precipitation (Pierce et al. 2004). A typical centroid-type algorithm is the Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN) (Dixon and Wiener 1993), which has been used in nowcasting systems throughout the world (many in Australia, South Africa, and Asia). The TITAN algorithm defines a storm cell as a contiguous region that exhibits reflectivity above a given threshold, and the volume of which exceeds a volume threshold. This definition of storm cells is also adopted in our study. Storm cells are also called storms in this paper for convenience.

The original TITAN algorithm uses a single threshold to identify storm cells. These storms are then tracked across consecutive radar scans using a combinatorial optimization method followed by an additional geometric algorithm to handle splits and mergers. Finally, TITAN uses the centroid displacement of the identified storm to make the short-term forecast of storm movement (Dixon and Wiener 1993). There have been several updates to the original TITAN algorithm since its invention. The TITAN system is now a relatively large suite of software, incorporating the capability to handle data from a large number of radar types, as well as supporting data from satellite, lightning sensors, surface observations, and numerical models (more information is available online at http://www.rap.ucar.edu/projects/titan/home/whatis_titan.php). The changes related to storm identification, tracking, and forecasting are listed as follows: the first change is that a dual threshold identification algorithm was added as an option. This dual threshold algorithm first uses a low threshold value to detect storm cells followed by application of a higher-valued threshold that is used to search for more intense cells within the envelope of the previously identified storm cells. Last, if there are two or more intense cells detected, a growth operation is performed on these intense cells until their edges touch or meet the original envelope identified by the lower threshold. Here, the growth operation is similar to the dilation operation, which will be described in the storm identification section below. The second change is that an overlapping technique was added in the tracking algorithm, followed by the existing combinatorial optimization method. The overlapping technique matches storms across consecutive scans by measuring the amount of overlap. To discriminate between these versions, we denote the most current TITAN algorithm as “updated TITAN” and the original TITAN algorithm as “original TITAN.” As the main body of updated TITAN is identical to original TITAN, we will still use the term TITAN unless it is necessary to discriminate between two algorithms.
When there are dense severe convective storms whose shape changes rapidly, or in the case that clusters of storms occur frequently, TITAN will exhibit the following difficulties. The first is storm identification. If the radar echoes are distributed densely, there will be false mergers and clusters of storms. The term “false merger” means two adjacent individual storms are treated by the identification algorithm as a single (merged) storm. The original TITAN algorithm is apt to identify a cluster of storms as one storm, and cannot handle the false merger problem. Updated TITAN uses two thresholds to identify cells and performs better than original TITAN. As will be illustrated in section 2 using schematic examples, more threshold levels can provide improved performance. The second difficulty is storm tracking. The combinatorial optimization method employed by the TITAN tracking algorithm uses a fixed maximum storm speed constraint that is apt to be incorrectly violated when the storm shape changes rapidly, leading to unexpected tracking errors. The TITAN algorithm calculates the storm cell speed based on the centroid displacement, which is not reliable and can exhibit speeds greater than the constraint. The random centroid displacement is caused by thresholding techniques used by the storm identification algorithm. The details will be described in section 3. The third difficulty is short-term forecasting. The TITAN algorithm uses the storm centroid displacement to forecast the storm motion, which may result in large errors from the actual storm movement if the shape of the storm changes rapidly. This error is also rooted in thresholding techniques.

To surmount these difficulties, this paper proposes an enhanced TITAN algorithm (ETITAN) that provides enhancements to the TITAN algorithm in three aspects. First, a mathematical morphology-based storm identification method (Dixon 1994; Han et al. 2007) is adopted that can mitigate the problem of false mergers and isolate adjacent storm cells within a cluster of storms. Mathematical morphology has proven to be a powerful tool for image analysis (Gonzalez and Woods 2002). Erosion and dilation are the two fundamental operations of mathematical morphology. Erosion of a set $A$, often representing the image of interest, by a set $B$ is given by

$$ A \ominus B = \{ z \mid (B)_z \subseteq A \} $$

The result is a new set of all points $z$ such that $B$, translated by $z$, is contained in $A$. The set $B$ is also called the structuring element or the convolution mask. The erosion operation on an image can be simply treated to shrink that image.

Dilation of a set $A$ by a structuring element $B$ is given by

$$ A \oplus B = \{ z \mid (\bar{B})_z \cap A \neq \emptyset \}. $$

The result is a new set of all points $z$ such that $\bar{B}$ and $A$ overlap by at least one element. The dilation operation on an image can be simply treated to enlarge that image.

This paper is organized as follows: section 2 describes the mathematical morphology-based storm identification method. Section 3 introduces the enhanced tracking and forecasting algorithms. Section 4 describes the analysis of case studies and results. Finally, conclusions are presented in section 5.

### 2. Storm identification

The original storm identification algorithm used in TITAN has two problems: 1) the false merger problem, and 2) the inability to isolate separate storms within a cluster of storms. The false merger problem indicates that two adjacent storms are treated by the identification algorithm as a single (merged) storm because of a weak connection in their reflectivity regions. A cluster of storms is defined here as a large storm with a number of stronger substorms within it. Figure 1 shows two schematic examples—a false merger and a cluster of storms, respectively. For convenience, we assume the storms in Fig. 1 have fixed reflectivity value (e.g., 35 or 40 dBZ).

It is necessary to introduce two important fundamental concepts of mathematical morphology, erosion, and dilation. These are presented next.

#### a. Definition of erosion and dilation

Mathematical morphology is a powerful tool for extracting image components that are useful in the representation and description of region shape, which has been used widely in image processing and analysis area (Gonzalez and Woods 2002). Erosion and dilation are the two fundamental operations of mathematical morphology.

Erosion of a set $A$, often representing the image of interest, by a set $B$ is given by

$$ A \ominus B = \{ z \mid (B)_z \subseteq A \}. $$

The result is a new set of all points $z$ such that $B$, translated by $z$, is contained in $A$. The set $B$ is also called the structuring element or the convolution mask. The erosion operation on an image can be simply treated to shrink that image.

Dilation of a set $A$ by a structuring element $B$ is given by

$$ A \oplus B = \{ z \mid (\bar{B})_z \cap A \neq \emptyset \}. $$

The result is a new set of all points $z$ such that $\bar{B}$ and $A$ overlap by at least one element. The dilation operation on an image can be simply treated to enlarge that image.
For the application of storm identification, the set $A$ can be treated as a storm located in the Cartesian grid, and $B$ can be simply selected as $3 \times 3$ pixels. For “merged” storms shown in Fig. 1a, the erosion result is shown in Fig. 2a. The weak overlap between two storms is eroded, leading to the correct identification of two storms. For the stronger substorms with reflectivity values of 40 dBZ in Fig. 1b, the dilation result is shown in Fig. 2b where substorms stop dilating when they meet the boundary of the large storm with reflectivity values of 35 dBZ.

Updated TITAN uses two thresholds set by users (typically 35 and 45 dBZ; see online at http://www.rap.ucar.edu/projects/titan/home/storm_identification.php) to identify cells and performs better than original TITAN. But updated TITAN cannot handle the problem of false mergers where two adjacent storm cells and their connection area have the same reflectivity (as shown in Fig. 1a). Besides, if 35 and 45 dBZ are selected as the thresholds, updated TITAN is also incapable of isolating individual substorms from the cluster of storms in Fig. 1b. This indicates that using more thresholds is necessary.

b. The identification algorithm

The ETITAN algorithm adopts a mathematical morphology-based storm identification method that can mitigate the problem of false mergers while maintaining the internal structure of the substorms acquired when isolating adjacent storms within a cluster of storms (Dixon 1994; Han et al. 2007). This method first applies a single threshold identification, followed by implementing an erosion process to handle the false merger problem. During multithreshold identification stages, the dilation and erosion operations are performed on the substorm cells that are just obtained by the higher threshold identification. The main steps are listed in Fig. 3.

To further illustrate the process, a schematic example depicting a cluster of storm cells with a false merger present is shown in Fig. 4. In this example, $T_{z,\text{min}}$ is set to 35 dBZ, and $N_{\text{thresh}}$ set to 2, which means there are two thresholds (35 and 40 dBZ). This example is described next:

1) Apply the single threshold identification process first, which is the same as TITAN, with the lowest threshold $T_{z,\text{min}}$. In short, the single threshold identification process includes three steps: identify contiguous sequences of points (referred to as runs) for which the reflectivity exceeds $T_{z,\text{min}}$; group runs that are adjacent on the same plane as the 2D component of cells; and group 2D components of cells on different planes as the 3D storm cells (Dixon and Wiener 1993). Figure 4a shows the identification result.
2) Perform the erosion operation on the storms identified at step 1 and get the output as shown in Fig. 4b. The merged storm splits into two isolated storms. False merger has been eliminated at the end of this step.

3) Within each storm in Fig. 4b, use the second threshold (40 dB\textsubscript{Z}) to extract stronger substorms. Two substorms with higher reflectivity (40 dB\textsubscript{Z}) are extracted as shown in Fig. 4c.

4) For each substorm in Fig. 4c, perform the dilation and erosion operations. The final result is shown in Fig. 4d. Two adjacent storms in a cluster of storms are isolated while the internal structure is well maintained.

It should be mentioned here that the Storm Cell Identification and Tracking (SCIT; Johnson et al. 1998) also used multiple thresholds (e.g., 30, 35, 40, 45, 50, 55, and 60 dB\textsubscript{Z}). In short, SCIT first uses the lowest threshold (30 dB\textsubscript{Z}) to identify storm cells and then increases the threshold gradually to identify more intense cells. The SCIT algorithm is capable of isolating adjacent storms within a cluster of storms but it has been shown to lose the internal structure of the storms since only the most intense (i.e., highest reflectivity-thresholded components) are used to define 3D storm cells; lower reflectivity-valued components are discarded if the centroid of the higher reflectivity-thresholded component falls within its area.

3. Storm tracking and forecasting

   a. Tracking enhancements using the overlapping and dynamic constraint techniques

   If there are multiple storm cells in a single radar volume scan when severe weather is present, the storm tracking problem becomes one of determining motion correspondence between storm cells in successive radar images (i.e., determining whether measurements taken at successive time steps result from similar or different storm cells). In the computer vision and target tracking community, this is also referred to as the data association problem (Bar-Shalom and Foreman 1988; Yilmaz et al. 2006). The overlapping technique has been added to updated TITAN followed by the combinatorial optimization method to handle the data association problem. The ETITAN algorithm also adopts the overlapping technique and then uses a dynamic constraint technique-based combinatorial optimization method.

   The overlapping technique assumes that if storm shapes at two successive times overlap significantly, these shapes are likely to be from the same storm (more information is available online at http://www.rap.ucar.edu/projects/titan/home/storm_tracking.php). Suppose that there are \( n_1 \) storms at time \( t_1 \) and \( n_2 \) storms at \( t_2 \), and the overlapping technique is as follows:
1) For each of the \( n_1 \) storms at \( t_1 \), make a forecast of the storm position at \( t_2 \) using the forecasting technique detailed in the next section.

2) If a forecasted storm shape overlaps with one of the \( n_2 \) storms at \( t_2 \), then calculate two overlap fractions for these two storms: \( f_1 \), the overlap area divided by the storm area at \( t_1 \); \( f_2 \), the overlap area divided by the storm area at \( t_2 \).

3) The association probability \( (p) \) between these two storms is given by \( p = (f_1 + f_2)/2 \). A perfect overlap will result in \( p \) of 1.0, and no overlap at all will result in \( p \) of 0.0. If \( p \) exceeds 0.5, the storms are considered to be part of the same track.

Since a storm at two consecutive scans may not overlap much (which may cause the overlapping technique to lose the correct track), the combinatorial optimization method based on a dynamic constraint is used, which is illustrated using the following example.

Suppose that there are \( n_1 \) storms at time \( t_1 \), \( n_2 \) storms at \( t_2 \), and \( \Delta t = t_2 - t_1 \). Figure 5 shows all possible associations between storms at \( t_1 \) and \( t_2 \). The problem is now how to determine the most likely correspondence between \( n_1 \) storms at \( t_1 \) and \( n_2 \) storms at \( t_2 \). Similar to TITAN, we define the objective function as follows:

\[
Q = \sum C_{ij},
\]

where \( C_{ij} \) is the cost when storm cell \( i \) at \( t_1 \) matches storm cell \( j \) at \( t_2 \), and

\[
C_{ij} = d_p + d_v,
\]

where \( d_p \) is the Euclidean distance between the centroids of the two projected storm cells and \( d_v \) is the cube root of the volume difference between the two cells.

In practice, constraints are imposed to limit the scope of the feasible solution set of the combinatorial optimization problem. In terms of storm tracking, a maximum speed constraint is imposed based on the maximum expected storm speed, \( S_{\text{max}} \). In this paradigm, an association match is considered feasible if \( d_p/\Delta t < S_{\text{max}} \). Within the subset of possible matches within this constraint, the solution that minimizes the objective function, \( Q \), is chosen.

In the TITAN algorithm, a fixed maximum speed constraint of \( S_{\text{max}} = 100 \text{ km h}^{-1} \) is imposed. While the maximum translational speed of storm cell centroids

![Fig. 4. Illustration of the identification method based on mathematical morphology. (a) Outputs of using the first threshold, (b) outputs after erosion, (c) outputs using the second threshold, and (d) outputs after dilation and erosion.]

![Fig. 5. All possible associations between storms at \( t_1 \) and \( t_2 \).]
falls within this constraint, experiments have shown that for storm cells with a large projected area (e.g., greater than 300 km²) where the shape changes significantly with time, the storm cell speed calculated by centroid translation is not reliable and can exhibit speeds greater than the constraint. But this violation does not mean that large storm cells really move so fast. The storm cell speed calculated by centroid translation sometimes does not reflect the real speed of the storm cell, especially for large storm cells. This phenomenon is rooted in thresholding techniques used by the storm identification algorithm. As shown in Fig. 6, for a storm cell at \( t_1 \), only those regions above the reflectivity threshold can be identified as “storms.” At \( t_2 \), if the left regions within the same storm exceed the threshold, the shape of the identified storm cell may change significantly, leading to a large centroid displacement. So it becomes necessary to apply a large maximum speed constraint for large storm cells to tolerate this random centroid displacement caused by thresholding techniques.

Based on the above analysis, a dynamic maximum speed constraint is used in the ETITAN algorithm. We make the following intuitive assumption: a storm cell with larger area is assigned a larger speed constraint. Note that if \( S_{\text{max}} \) is fixed to a value that is too large relative to the storm cell area, distant storm cells can be selected as matches leading to tracking failure. The dynamic strategy is, when a storm area is less than 300 km², \( S_{\text{max}} \) is set to 100 km h⁻¹; when a storm area is between 300 and 500 km², \( S_{\text{max}} \) is set to 150 km h⁻¹; when the area is larger than 500 km², \( S_{\text{max}} \) is 200 km h⁻¹. It should be mentioned that this strategy does not mean that large storm cells are assumed to move faster than smaller cells. A storm cell of a larger area is given a higher maximum speed constraint to tolerate the random centroid displacement caused by thresholding techniques, as described in the previous paragraph. Once this dynamic constraint is established, the Hungarian method (Dixon and Wiener 1993) is used to solve the combinatorial optimization problem as is done in the original TITAN algorithm.

b. Composite motion vector field–based storm forecasting

The TITAN algorithm calculates the storm velocity based on the reflectivity-weighted centroid displacement, which may cause unreliability. This is also caused by thresholding techniques described in the previous section. As shown in Fig. 6, the shape of storm cells can change rapidly, causing random displacement of the storm cell centroid. This can cause large deviation from the correct centroid velocity, leading to tracking errors. The use of linear regression for extrapolation forecasting to fit data from the past time steps helps to smooth out errors in the centroid position. However, if a major error in the centroid position occurs, this smoothing method will cause the error to affect a number of time steps beyond that at which the error occurred.

The strength of the cross-correlation method is that it provides more accurate speed and direction information of the reflectivity echo, while the strength of the centroid tracking method is to identify and track individual isolated storms (Johnson et al. 1998). The ETITAN algorithm combines the benefits of two methods by using the motion vector field, calculated by TREC, to forecast the movement of individual isolated storm cells.

The forecasting algorithm is summarized here:

1) The TREC algorithm is applied to the composite reflectivity field to generate a motion vector field representing field motion for the most current radar scan. The composite reflectivity field can be treated as a 2D grid, where each grid value is calculated as the maximum reflectivity at any height in the 3D Cartesian grid.
2) The average value of the motion vector field (\( V_{\text{trec}} \)) within the area of the identified cell is calculated.
3) The storm cell position is forecasted using \( V_{\text{trec}} \) and the cell centroid. Other parameters (e.g., top, base, volume, etc.) are forecasted using the original TITAN algorithm.
4. Analysis of case studies and results

a. Data processing

The radar data for case studies were collected by the S-band Doppler radar at Tanggu, Tianjing, China, which is a prototype similar to the Weather Surveillance Radar-1988 Doppler (WSR-88D). The radar site is located at (117°43'E, 39°00'N), 100 km southeast of Beijing, China. The sampling rate is one volume scan per 6 min using the volume coverage pattern (VCP) 21 mode. All images shown in this section are composite reflectivity images. The radar base data are processed in the same way as TITAN. The original radar coordinate data are transformed into Cartesian coordinates. Noise and ground clutter are filtered out (Dixon and Wiener 1993). The horizontal spatial resolution of the Cartesian grid is 0.01° × 0.01° (about 1 km × 1 km). There are 20 layers, or CAPPIs, from 0.5 to 19.5 km with the vertical resolution 1 km.

b. Storm identification

The Tanggu radar collected data from a severe convective weather event that occurred from 1300 to 2000 LST 31 May 2005. This weather event was caused by a meso-γ-scale convective system with multiple storms producing hail. We use this dataset for identification studies. And the lowest threshold, \( T_{z,min} \), is set to 40 dBZ because it was severe convection. For ETITAN, \( N_{\text{thresh}} \) is set to 5. And for updated TITAN, 40 and 45 dBZ are used.

Figure 7 shows a composite reflectivity image of this storm event (1729 LST 31 May 2005). Several adjacent storm cells are seen north of the radar station in this image. The storm cell identification results from original TITAN, updated TITAN, SCIT, and ETITAN are shown in the associated figures. Figure 7a shows the case of a false merger using the original TITAN algorithm (see the white arrow). The separate storm cells contained within the white rectangle are considered one cell by the original TITAN algorithm. Figure 7b shows the results of updated TITAN. The cells contained within the white rectangle are considered two cells now. This is better than the result of original TITAN. Figure 7c shows the results of the SCIT algorithm. It is apparent that the storm cell labeled as “1” is not identified because SCIT only considers the most intense components when the centroid of a higher-reflectivity-thresholded component falls within the area of a lower-reflectivity-thresholded component. Also, the cell identification of those cells within the white rectangle is incomplete, resulting in a loss of information of the storm structure within this region. Figure 7d shows that ETITAN correctly identifies storm cells “1” and “2” and isolates and preserves three storm cells contained in the white rectangle.

In the following time steps, storm cell 1 grew rapidly while cell 2 decayed rapidly. Figure 8 shows the evolution of both cells identified by ETITAN at four successive scans (1729, 1735, 1741, and 1747 LST 31 May 2005). The correct identification of the false merger has another advantage in that it can provide useful visual information for forecasters. At 1729 LST, either the false merger result given by original TITAN or the missing result given by SCIT tends to cause forecasters to neglect the fast growing nature of cell 1. It should be noted that although TITAN gives the false merger result, cell 1 can still be forecasted along with cell 2 as a merged cell. Thus the short-term forecast evaluation scores of TITAN may not differ much compared to the scores of ETITAN, which can correctly identify cells 1 and 2.

In the following section, storm tracking and forecasting performance is evaluated between TITAN and ETITAN.

c. Storm tracking and forecasting

Figure 9 shows a violation of the storm maximum speed constraint. The shape of the storm cell labeled as 3 changed sharply. At 1811 LST 24 June 2006, the projected area of the cell was 2677 km² with the reflectivity centroid located at (40.26°N, 118.25°E). Six minutes later, the projected area increased to 3036 km² with the reflectivity centroid located at (40.27°N, 118.42°E). The very irregular and rapidly changing shape causes a large centroid speed (140 km h⁻¹), which violates the maximum speed constraint leading to tracking errors (e.g., cell 3 is terminated at 1811 LST and is treated as a newly born cell at 1817 LST). For the cell 3 with area larger than 500² km, the dynamic speed constraint is set to 200 km h⁻¹, which facilitates the correct tracking. And it is obvious that the overlapping technique can also correctly track the cell 3 with the association probability 0.72.

Next, we illustrate a comparison of forecasting performance between TITAN and ETITAN. Figure 10 shows a supercell that was observed at 1627 and 1645 LST 24 June 2006. Figures 10a and 10b depict the forecasting outputs of TITAN and ETITAN at 1627 LST. The TITAN algorithm predicted southward motion, while ETITAN predicted eastward motion. The observed storm position at 1645 LST is shown in Fig. 10c, showing eastward movement and thus illustrating an erroneous TITAN forecast.

A more thorough evaluation of the identification, tracking, and forecasting performance of TITAN and ETITAN is given in section 4d.
d. Quantitative evaluation of short-term forecasting performance

The contingency table approach (Donaldson et al. 1975) is used to quantitatively evaluate the short-term forecasts. The probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI) are calculated for each dataset. The evaluation is performed based on a common grid onto which both the forecast storm position and the actual radar echoes at the forecast time are mapped. At each grid point, a success (S) occurs when both truth and forecast grid points exceed
the reflectivity threshold $T_{z,\text{min}}$, a failure ($F$) occurs when the truth point is active while the forecast point is inactive, and a false alarm ($A$) occurs when the truth point is inactive while the forecast point is active. Thus, $\text{POD} = S/(S + F)$, $\text{FAR} = A/(S + A)$, and $\text{CSI} = S/(S + F + A)$ (Dixon and Wiener 1993).

Three methods are compared: original TITAN, updated TITAN, and ETITAN. Compared to original TITAN, updated TITAN adds the dual threshold and overlapping techniques. Data from twelve days that are classified into three categories (Johnson et al. 1998) were analyzed:

1) Isolated storm. Storm cells are predominantly isolated. Splits and mergers seldom happen and there are no large clusters of storms. In this category, storm cells are easy to identify and track. Data from 4 days are selected: 27 July 2003, 23 June 2004, 31 May 2005, and 9 September 2007. The $T_{z,\text{min}}$ is set to 40 dBZ for three methods and $N_{\text{thresh}}$ is set to 5 by ETITAN for all three categories.

2) Mesoscale convective system (MCS)/line. Individual storms are in a large cluster or squall lines. This category represents those storm cells that are difficult to identify and track. Four cases are selected:

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**Fig. 9.** Illustration of violation of the maximum speed constraint. (a) At 1811 LST 24 Jun 2006, the projected area of storm cell 3 was 2677 km$^2$ with the reflectivity centroid located at (40.26°N, 118.25°E). (b) At 1811 LST, the projected area of storm cell 3 was 3036 km$^2$ with the reflectivity centroid located at (40.27°N, 118.42°E). The storm speed calculated using the centroid displacement is 140 km h$^{-1}$, violating the maximum speed constraint of 100 km h$^{-1}$.

**Fig. 10.** Eighteen-minute forecast using (a) TITAN and (b) ETITAN at 1627 LST 24 Jun 2006. (c) The observed storm position at 1645 LST. The brown curves represent the boundaries of the identified storm cells. The cyan curves are the 18-min forecast of storm cell size and position.
3) *Stratiform precipitation*. The radar echo is a large area of light–moderate reflectivity with few if any reflectivity values above 40 dBZ. The TITAN algorithm was not originally designed for stratiform precipitation cases. The evaluation results will show that ETITAN also achieved significant improvements for these stratiform events. The last four cases are 22 June 2003, 16 June 2004, 26 May 2006, and 30 June 2007. The $T_{z,\text{min}}$ was set to 35 dBZ.

The scoring results for the 18-min forecasts are shown in Fig. 11. For every category, values of POD, FAR, and CSI are the average values for all the cases belonging to that category. For all three categories, ETITAN and updated TITAN achieved similar scores. The reasons may be to the scoring improvement. ETITAN and updated TITAN algorithms (identification, tracking, and forecasting), to show their enhancements. ETITAN and updated TITAN algorithms have no chance directly identifies and tracks an isolated storm cell, then and track for all three methods. If original TITAN correct prediction, that implies that an old storm will be identified and tracked using a new storm that category. For all three categories, ETITAN and updated TITAN achieved significant performance improvements as compared with the original TITAN algorithm.

For the isolated storm category, the difference in the scoring results of the three methods is not so large compared to the other two categories. This is to be expected since isolated storms are relatively easy to identify and track for all three methods. If original TITAN correctly identifies and tracks an isolated storm cell, then ETITAN and updated TITAN algorithms have no chance to show their enhancements.

It should be mentioned that among the three sub-algorithms (identification, tracking, and forecasting), the tracking algorithm enhancements contribute most to the scoring improvement. ETITAN and updated TITAN achieved similar scores. The reasons may be explained as follows:

1) The new identification method can provide more accurate results, but the contingency table approach does not distinguish the correct and incorrect identification results. As described in the storm identification analysis section, the incorrect identification of the false merger or a cluster of storms may not have much impact on the forecasting evaluation scores in the scheme of the contingency table approach. But this does not affect the importance of giving correct identification results.

2) For the 18-min forecasts, updated TITAN achieved an improvement of average CSI by 13% as compared with original TITAN. As previously stated, the new identification method including the dual threshold technique does not impact the evaluation scores much. Then the contribution of this improvement is mainly from the overlapping technique. Actually, experiments of the above 12 cases have shown that the overlapping technique is a powerful and effective addition to the TITAN tracking scheme, which dramatically cuts down on the number of errors. This leaves the dynamic constraint-based combinatorial optimization method less chances to show further enhancement.

3) As Wilson et al. (1998) stated, “the major cause of poor extrapolation forecasts is not due to errors in forecast displacement, but to decay and growth occurring during the forecast period.” The ETITAN algorithm is an extrapolation method and is also incapable of accounting for storm initiation and dissipation. Embedding the TREC motion vector field does help ETITAN to improve the nowcasting performance, but it is reasonable that the scoring results do not improve too much. Another advantage of incorporating the TREC motion vector field into ETITAN is that it can provide useful information of storm motion for forecasters. Figure 10 has shown such a case. Relatively speaking, the tracking failure has much impact on the forecasting evaluation scores. If a tracking failure occurs, that implies that an old storm will be treated as a newly born storm. Thus a complete storm track may be divided into numerous parts, which will heavily impact the short-term forecasting.

5. Conclusions

This paper proposes enhancements to the TITAN storm identification, tracking, and forecasting algorithm. In the storm identification stage, this enhanced algorithm, ETITAN, was shown to better handle the false merger problem and isolate individual storms within a cluster of storms using a multithreshold mathematical morphology method. Two morphology operations, erosion and dilation, are used iteratively during multithreshold identification stages while the original TITAN (original TITAN) only uses one threshold, and the most current TITAN (updated TITAN) uses two thresholds to identify storms. In the storm-tracking stage, ETITAN uses an overlapping technique that has been added into updated TITAN and a dynamic constraint protocol in a
Fig. 11. (a) POD, (b) FAR, and (c) CSI for the 18-min forecasts for the indicated categories (labeled below the bars), and the average for all the cases (extreme right).
combinatorial optimization model to track storm cells. To tolerate the random centroid displacement, which is rooted in thresholding techniques used by the storm identification algorithm, the maximum storm speed constraint is dynamically set according to the area value of each storm cell. Finally, ETITAN uses the motion vector field computed from the TREC algorithm to forecast the later position of the isolated cells, while TITAN makes forecasts based on the storm centroid displacement. Qualitative analysis showed that ETITAN achieved better performance than both original and updated TITAN and it can provide more useful information for forecasters. Quantitative short-term forecasting evaluation results showed that both ETITAN and updated TITAN achieved significant improvements compared with the original TITAN algorithm. For the 30-min forecasts, ETITAN had an average CSI of 0.29 as compared with 0.28 for updated TITAN and 0.15 for

![Graphs showing 30-min forecast for POD, FAR, and CSI](image)

**Fig. 12.** Same as in Fig. 11, but for the 30-min forecasts.
original TITAN. Updated TITAN and ETITAN apparently perform better than original TITAN for the MCS/line and stratiform precipitation categories. For the isolated storm category, three algorithms achieved similar performance since isolated storms are relatively easy to identify and track. For all the categories, ETITAN and updated TITAN achieved similar scores. The reasons for this are also analyzed: 1) the new morphology identification method does not have much impact on the forecasting evaluation scores in the scheme of the contingency table approach; 2) the overlapping technique is powerful and leaves less chances for the dynamic constraint-based combinatorial optimization method to show further enhancement; and 3) the composite motion vector field–based forecasting method does help ETITAN to improve the nowcasting performance, but this improvement is limited since ETITAN cannot account for storm initiation and dissipation, which is the major cause of poor extrapolation forecasts.

As stated in this paper, thresholding techniques used by the storm identification algorithm may cause unreliability in tracking and forecasting stages. In future work, it is necessary to research a new identification algorithm that is not dependent on thresholding techniques. This research may benefit from the studies of object detection in the computer vision community (Yilmaz et al. 2006).

Acknowledgments. This work was supported by the Open Research Project of the State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences under Grant 2008LASW-A02 and the Ph.D. Programs Foundation of the Ministry of Education of China under Grant 20040001008. The authors thank Dr. Mike Dixon of NCAR for providing information of TITAN and fruitful discussion and suggestions.

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