Determination of the Boundary Layer Airflow from a Single Doppler Radar

JOHN D. TUTTLE AND G. BRANT FOOTE

National Center for Atmospheric Research,* Boulder, Colorado
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ABSTRACT

In the warm season the optically clear boundary layer often contains scatterers that can be detected by sensitive radars to distances of 50–100 km. Inhomogeneities in the field of reflectivity lead to echo patterns that have some persistence over periods as long as 5–10 minutes. These echo patterns translate with the local wind and can, for example, be easily followed by eye on PPI playback loops reviewing 15–20 minutes of data. In this paper a technique is discussed that determines the wind field by objectively identifying and tracking local echo patterns. The technique, called TREC (Tracking Radar Echoes by Correlation), involves the cross-correlation of the echo features measured at two times a few minutes apart. The translation of a local feature during the measurement interval then determines the local wind. Use of this technique in the clear boundary layer means that problems associated with noisy data (reflectivities just above the minimum detectable signal) and ground clutter will be common. A number of methods for dealing with these matters are presented. The use of TREC in clear air rather than in storms carries the advantage that misleading results associated with the sedimentation of hydrometeors in a sheared flow are avoided.

In this study TREC is applied to data collected during the Convective Initiation and Downburst Experiment (CINDE) in northeastern Colorado. The method is shown to provide horizontal winds in the boundary layer (the region of significant clear-air echo) over areas 100 to 150 km on a side with a resolution of about 10 km. TREC can be used with either conventional or Doppler radars sensitive enough to detect clear-air echo, though there are some advantages in using single Doppler measurements to improve the reliability of the technique. Applications of the present method are anticipated in a number of research and forecast areas.

1. Introduction

The structure of the planetary boundary layer and its influence on convective clouds have been longstanding topics of investigation. Using a dense network of anemometers during the Thunderstorm Project, Byers and Braham (1949) often observed convergence lines 20–30 minutes prior to the first radar echo associated with deep convection. Other studies have shown the role that land-sea breeze interactions play in initiating convection along the Florida coast (Gentry and Moore 1954; Burpee 1979; Cooper et al. 1982; Watson and Blanchard 1984). Recent studies using comprehensive data sets including mesonet, Doppler radars, satellite and sounding information continue to document the importance of boundary layer interactions (Wilson and Schreiber 1986; Schreiber 1986; Szoke and Brady 1989). For example, of the 418 storms that initiated within their study area in northeast Colorado, Wilson and Schreiber found that 79% formed in close proximity to radar-observed convergence lines. These convergence lines were often associated with the Denver Cyclone, a mesoscale zone of low-level convergence and vorticity that usually forms in the Denver area under conditions of south to southeast ambient flow (Szoke et al. 1984; Benjamin et al. 1986; Wilczak 1987). Climatological studies have shown that the chance of severe thunderstorm activity is enhanced when the Denver Cyclone is present (Szoke et al. 1984; Szoke and Brown 1987).

Given this background it is not surprising that real-time boundary layer measurements are becoming a key element in the short-range forecast of severe weather. For example, in the Program for Regional Observing and Forecasting Services (PROFS) an assortment of measuring systems, including radar, sounding, surface mesonet and satellite, are integrated and displayed in real time to improve the reliability of nowcasts (Schlatter et al. 1985).

Of the measuring systems that provide information on the structure of the boundary layer, radar is particularly well suited, being able to sample over large areas with good spatial and temporal resolution. Previous studies have employed multiple-Doppler networks to obtain boundary layer airflow, either by dispensing chaff to provide radar echoes (Schneider and Lilly 1986; Kropfli et al. 1986) or by using radars sensitive

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Corresponding author address: Mr. John Tuttle, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307.

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enough to detect clear-air return (Berger and Doviak 1979). Because the editing and analysis of multiple-Doppler data is usually tedious and requires that data be on a common grid, however, analyzing large amounts of data over long time periods is difficult. To date such analysis has not been done in real time. Furthermore, unless a large Doppler network is used, wind information is obtained only over a relatively limited area.

An alternative approach is to employ the technique of pattern recognition using cross-correlation analysis. In this method the cross-correlation of radar echo patterns measured several minutes apart is calculated to determine their translational motion. In early work this method was used to determine the motions of entire storm cells (Hilstr and Russo 1960; Kessler and Russo 1963; Crane 1979; Bjerkasaas and Forsyth 1980). More recently, with the availability of higher resolution data, the technique has been extended to obtain the internal motions of precipitating clouds (Rinehart and Garvey 1978; Rinehart 1979) and airflow in the boundary layer (Smythe and Zrnić 1983). The primary advantage of the technique is that it only requires a single radar and information can be obtained in all directions from the radar wherever there are detectable echoes. A major drawback is that it follows the motions of echo patterns that may not necessarily represent the air motion. Rinehart (1979) compared results from his correlation analysis called TREC (Tracking Radar Echo by Correlation) to dual-Doppler derived winds and found important differences. These were attributed primarily to the sedimentation of the scatterers in the presence of vertical shear, strong vertical motions, and the rapid growth of precipitation that characterize convective cloud systems. In applying the technique to clear-air return in the boundary layer, as reported by Smythe and Zrnić (1983), these problems are largely avoided. Indeed, Smythe and Zrnić found good agreement between the motions derived from cross-correlation analysis and the dual-Doppler winds, although the study was done only on a simple, almost uniform flow field.

In this study we explore further the potential of using the cross-correlation technique on clear air echoes and discuss a variety of data quality issues. The nature of the phenomenon being sampled, (echoes with low signal-to-noise ratios concentrated near the surface) dictates that ground clutter and noisy data will be matters for concern. Methods for dealing with these issues are presented. Using examples, it is demonstrated that the technique can derive the boundary layer airflow over areas 100–150 km on a side and for time periods of several hours with relative ease.

2. Technique

The technique used in this study for the computation of pattern translation vectors, TREC, is that of Rinehart (1979) and will only be described briefly here. In this technique one stores two PPI scans of either reflectivity or radial velocity measured at the same elevation angle and at times separated by several minutes. The analysis proceeds by dividing the first scan into a number of equal-sized two-dimensional arrays or “boxes” spaced some distance apart. Each initial array is then correlated with all possible arrays of the same size in the second scan to find the best matching second array, i.e., to determine the initial array–second array pair that has the highest correlation coefficient. The location of this second array determines the endpoint of a translation vector as shown in Fig. 1. Both the array size and spacing are inputs to the program. The array size, though chosen somewhat arbitrarily, is bounded by two extremes. If made too large, resolution is sacrificed and only the mean flow is found; if too small the array will not contain enough data points to determine a stable correlation coefficient. We have found array sizes of 3 to 7 km to be optimum. For the data resolutions typically achieved by modern radar (150–250 m range gate spacing, 1° azimuth spacing) an array will contain around 100–500 data points.

The two-dimensional array $Z(r, \theta)$ in radar coordinates of range and azimuth is represented as a one-dimensional array $Z(i)$ by rearranging rays of data head-to-tail in the obvious way. The correlation coefficient, $R$, is then calculated using

$$ R = \frac{\sum Z_1(i)Z_2(i) - n^{-1}\sum Z_1(i)\sum Z_2(i)}{\sqrt{\left[\sum Z_1^2(i) - n\bar{Z}_1^2\right]\left[\sum Z_2^2(i) - n\bar{Z}_2^2\right]}} $$

where $Z_1$ and $Z_2$ are the arrays of scalar data (either reflectivity or radial velocity) from scans 1 and 2, respectively, and $n$ the number of data points within an array. To avoid searching the entire dataset for the best matching second array, a limited search radius, $r$, is specified around each initial array by $r = V\Delta t$ where $V$ is the maximum velocity expected and $\Delta t$ the time between scans (see Fig. 1). The value of $V$ is arbitrarily chosen based upon mesonet or sounding information or from what one would reasonably expect given the situation.

Figure 2 shows an example of the field of correlation coefficients obtained. The maximum value, $R_{max}$, is found by interpolation. The position of this maximum then constitutes the head of the translation vector, as shown in Fig. 2.

The correlation coefficient field in Fig. 2 shows a drop-off from $R_{max}$ to 0.5 $R_{max}$ in a distance of about 1 km, a result typical for the clear-air reflectivities considered here. In using the TREC technique to obtain internal storm motions, Rinehart’s (1979) results gave values closer to 3 km. This difference, and the typically larger correlation coefficients found in Rinehart’s study, reflect the greater degree of fine structure and the more rapid evolution of the clear-air return compared with
precipitation echoes, which have a larger scale organization that is more persistent.

3. Editing of vectors

The present analysis differs from that of Rinehart (1979) in the type of data used and in the editing procedures employed. In applying TREC to precipitating clouds Rinehart specified a minimum signal below which no processing was attempted to avoid having to deal with noisy data. In the present application of TREC to clear-air return, the signal is often close to the noise level, but the correlation analysis is nevertheless carried out everywhere in order to extract as much information as possible. This means that noise will often contaminate the signal, particularly at long ranges from the radar and near the top of the boundary layer. Sampling the weak echoes at low elevation angles also means that ground clutter will likely be a problem; in fact, TREC is found to be quite sensitive to ground clutter contamination.

We illustrate these effects by considering an example of TREC output based on data collected at 1302:01 and 1307:21 (MDT) on 2 July 1987 during the Convective Initiation and Downburst Experiment (CINDE) near Denver, Colorado (Wilson et al. 1988). At this time only clear-air echoes were present having magnitudes of 0–15 dBZ. Above the boundary layer the clear-air return quickly dropped below the radar minimum detectable signal. The National Center for Atmospheric Research (NCAR) CP-3 Doppler radar reflectivity data were used in the correlation analysis. Figure 3 shows the location of CP-3 and the topography of the field experiment area. The north–south line of the Front Range can be seen to the west of Denver and to the south an east–west ridge of higher terrain, the Palmer Ridge.

![Figure 1: Schematic showing the computation of a TREC vector to determine the motion of reflectivity echoes (shaded) from TIME 1 to TIME 2. The initial array of data at TIME 1 is cross-correlated with all other second arrays of the same size at TIME 2 whose center falls within the search area. The position of the second array with the maximum correlation determines the vector endpoint. In this study the array size used was 7 km and the time between measurements was typically 5 minutes.](image1)

![Figure 2: Contours of correlation coefficient between first and second arrays computed at each of the points shown. These points each constitute the center of a "second array" as well as being a subset of the positions of the original Z(r, θ) measurements. A 7 km by 7 km array was used for the calculations, containing 392 points. The bold arrow extends from the center of the initial array to the maximum correlation coefficient (found by interpolation), and constitutes the pattern translation vector. Dividing this by the time interval between scans gives the TREC velocity vector.](image2)
Figure 3 shows fields of TREC vectors, $R_{\text{max}}$ and Doppler velocity spatial variance, $\sigma^2$, and a scatter plot of the radial component of the TREC vector, $V_{TR}$, versus the average Doppler radial velocity, $\bar{V}_D$. The $\bar{V}_D$ is an average of the Doppler velocity measurements within an array and $\sigma^2$ the variance of the measurements. We will be showing the $V_{TR} - \bar{V}_D$ scatter plots as a means of determining how well the TREC vectors are in agreement with the airflow. If there is good correlation between $V_{TR}$ and $\bar{V}_D$, one would expect that the tangential component of the TREC vector should be accurate also. This provides an easy way to assess the TREC vector quality without having to do a complete multiple Doppler analysis.

With the exception of a few vectors an almost uniform southeasterly flow is indicated over the entire area and $R_{\text{max}}$ values are generally in the range 0.4 to 0.7. The exceptions are at ranges greater than about 90 km where the vectors become noisy (northeast and southeast corners of Fig. 4a) and an area of vectors having near zero magnitudes within a radius of about 25 km of the radar. These same features can be identified in the scatter plot (Fig. 4d). The majority of the scatter points lie near the one-to-one line, i.e., the TREC radial components are in close agreement to the measured Doppler velocities. A few points lie some distance to either side of the one-to-one line having near zero Doppler velocities. These correspond to the noisy TREC vectors at long ranges. The zero TREC vectors can be seen as a distinct horizontal line of points having $\bar{V}_D$ values between $\pm 5$ m s$^{-1}$. A total of 726 vectors were calculated and the correlation coefficient, $R_c$, between $V_{TR}$ and $\bar{V}_D$ was 0.57.

Considering first the obviously erroneous, noisy vectors, it can be seen that most are associated with $R_{\text{max}} < 0.25$ and $\sigma^2 \gg 10$ to $15$ m$^2$ s$^{-2}$. At a range of 90 km the radar beam is scanning near the top of the boundary layer. This together with the range-squared dependence of the radar minimum detectable signal results in low signal-to-noise ratios, and the cross-correlation is thus being done on noisy data. This results in low $R_{\text{max}}$, high $\sigma^2$ and $\bar{V}_D$ values that tend toward 0. By thresholding either on the correlation coefficient or the variance or both, many of the noisy vectors can be removed. Figure 5 shows the vector and $V_{TR} - \bar{V}_D$ scatter plots when thresholding the vectors in Fig. 4 on $R_{\text{max}} = 0.25$ and $\sigma^2 = 12$ m$^2$ s$^{-2}$ (vectors with $R_{\text{max}} < 0.25$ or $\sigma^2 \gg 12$ m$^2$ s$^{-2}$ are discarded). A comparison with Fig. 4a shows that most of the noisy vectors have been removed (128 vectors were removed) and $R_c$ has increased to 0.71. Although we chose to threshold on both $R_{\text{max}}$ and $\sigma^2$, using either threshold alone would have produced nearly the same results. Both $R_{\text{max}}$ and $\sigma^2$ depend directly upon the noisiness of the data.

At ranges close to the radar, ground clutter contaminates the clear-air signal. A comparison of the CP-3 ground clutter map (Fig. 6) shows that most of the zero vectors are in regions of ground clutter. Ground targets are stationary, highly correlating signals which dominate any clear-air return that might be present, and results in TREC vectors of zero magnitude. As would be expected many of these vectors have high $R_{\text{max}}$ values, generally greater than about 0.7 (compare Fig. 4a with 4b). Thus it seems reasonable that many of the vectors affected by ground targets could be removed by thresholding on high value of $R_{\text{max}}$. The effect of thresholding on $R_{\text{max}} = 0.7$ (vectors with $R_{\text{max}} \geq 0.7$ discarded) is shown in Fig. 7. Many of the zero TREC vectors have been removed (108 additional vectors were removed) although several small areas of zero vectors still remain. The primary result of the process was to remove those zero vectors which also had $\bar{V}_D$ values of around 0 (compare Fig. 7b with 5b). Thus many of the remaining zero TREC vectors, which are presumably due to ground clutter, are in areas of non-zero Doppler velocities.

To explore this apparent discrepancy we investigated the effects of ground clutter on TREC by artificially introducing ground targets in an area where only clear-air return existed. We modeled a ground target by specifying its location, maximum reflectivity and radius and then fitting a second-order curve to the target reflectivity as a function of distance from its center. The radius was defined as the distance from the target center to where the target reflectivity fell to the minimum detectable. The target was sampled at the original azimuth angles and its reflectivity added to the original data. TREC was then applied to the new data set. The results are shown in Fig. 8 for the case of no ground target and ground targets of 0.5 and 1.0 km radius centered at $x = 45, y = 5$ km. The dataset is the same as used above except the plot area has been reduced.
to 30 km × 30 km to show details of the results. In the situation of no ground target the vectors show southeasterly flow of around 5 m s⁻¹ everywhere except in the area of x = 50 to 55 km and y = −10 to 0 km where natural ground targets are indicated by the zero vectors. $R_{\text{max}}$ values are around 0.45 to 0.6 (Fig. 8a). When the ground target is added three to four vectors near the target become 0 and $R_{\text{max}}$ increases to around 0.65 and 0.85 for the 0.5 and 1.0 km targets, respectively (Figs. 8c,e). The reflectivity plots (Figs. 8d,f) show dramatically just how small and innocuous a ground target can be and still influence TREC significantly. For example, the 0.5 km target affected at most about 2% of the reflectivity data points in any one 7 km array, but three vectors were still 0. In such a situation the TREC vector can be 0 while $V_T$ in the same array, being areally averaged, is hardly affected. Thus while the effects of large ground targets can be controlled by employing a high $R_{\text{max}}$ threshold (the 1.0 km target also would have been removed using the earlier threshold of 0.7), small isolated targets are not so easily treated.

Through the process of thresholding vectors on $R_{\text{max}}$ and $\sigma^2$, a fairly clean dataset was obtained (Figs. 7).
Fig. 5. (a) TREC vectors and (b) $V_{TR}$ vs $\bar{V}_D$ for the same dataset shown in Fig. 4 except vectors with $R_{min} < 0.25$ or $\sigma^2 > 12$ m$^2$ s$^{-2}$ are discarded.

Fig. 6. CP-3 reflectivity PPI at elevation = 0.9° showing ground clutter pattern. Reflectivity contours start at 15 dBZ and increment by 10 dB.
Can one do better? A few vectors still do not seem to fit in with their neighbors and on the scatter plot a few points lie some distance from the one-to-one line. Some of these, as we have seen, are due to small, isolated ground targets while others have significant magnitude and appear to be random. It is reasonable at this point to further threshold the vectors on the absolute value of the difference between $V_{TR}$ and $V_{PD}$, $\delta V = |V_{TR} - V_{PD}|$. That is, we reject vectors which have a $\delta V$ larger than some threshold. Figure 9 shows the vectors in Fig. 7 thresholded on $\delta V = 3$ m s$^{-1}$. Now we are left with an essentially clean data set. Thresholding on $\delta V$ eliminated an additional 57 vectors and increased $R_c$ to 0.94.

In any scheme to filter out bad data, there will inevitably be a gray area where some good data are thrown out with the bad. The case here is no exception. We subjectively judged each vector to be good or bad by visually comparing it with its neighbors and the general flow pattern. Of the vectors that remained after thresholding, 32 were considered to be bad. Altogether 293 vectors were discarded. Of these, 65 (22%) were judged to be good. These failure rates are not particularly bothersome, especially since many of the remaining bad vectors can be removed and data holes filled using methods similar to those in CEDRIC (Mohr et al. 1986).

At this point a final enhancement of the remaining vectors could be made by combining $V_{PD}$ with the TREC tangential components; i.e., allowing the Doppler measurements to describe the radial component of motion and TREC the tangential component. This was done routinely during the analysis. In nearly all cases the effects were small and did not represent a noticeable improvement.

The behavior of TREC in the presence of precipitation deserves special comment. Figure 10 shows the vectors obtained two hours later than the previous figures, with storm echoes now present. The data thresholding previously described was applied to remove noisy vectors. The southeasterly flow is still evident over much of the area and has strengthened in the southeast quadrant. In and near the precipitation echoes, however, the vectors appear chaotic with some suggestion of eastward movement in the southern cell. The scatter plot (Fig. 10c) shows considerably more scatter than before with an $R_c$ of only 0.42. If the data are thresholded on $\delta V = 3$ m s$^{-1}$ most of the vectors in the precipitation echoes are eliminated (Fig. 10d) suggesting that those vectors are not in good agreement with the airflow. The problem with using TREC on precipitation echoes is that the pattern being tracked is often generated at levels above or below the tracking level and the vectors determined tend to be the mean advection velocity of the storm or the generating cell rather than the airflow. Thus if TREC is used to derive the internal airflow of precipitating clouds, caution must be used.

4. Examples of derived wind fields

In section 3 methods for editing the TREC vectors were presented. We now wish to demonstrate the utility of TREC in obtaining a time series of boundary layer flow fields for a more complicated case.

Thus far all of the analyses have been done in polar
Fig. 8. TREC vectors (left panels) and CP-3 radar reflectivity (right panels) for the same dataset shown in Fig. 4. Panels (a) and (b) show the original data and panel pairs (c)–(d) and (e)–(f) show results when artificially adding a ground target at $x = 45$, $y = 5$ km of 0.5 and 1.0 km radius, respectively. $R_{\text{max}}$ of the vectors is indicated at the beginning point of each arrow. Reflectivity contours start at 5 dBZ and increment by 10 dB. The open arrow in (d) indicates the position of the artificial ground target.
space, i.e., on conical surfaces. For operational purposes this is perfectly adequate, but for research it is more desirable to have the data organized on horizontal planes. To do this TREC was run on several different pairs of elevation angles to obtain a volume of vectors. The vector, $R_{max}$, $\sigma^2$ and $\delta V$ fields were saved for use as input to an interpolation program. The data were interpolated to a Cartesian grid using an exponential weighting function. Since the data density was about 4–5 times more coarse in the horizontal than the vertical, we specified different radii of influence in the two directions, typically about 4 km in the horizontal and 0.4 km in the vertical. During the interpolation process it was important that noisy and bad vectors not influence a grid point, so the editing procedures described previously were first applied. The Cartesian data were saved in a standard format (the CEDRIC format described by Mohr et al. 1986) allowing for easy manipulation of the data using standard software (e.g., data smoothing and filling, computation of convergence, integration to obtain vertical motions, merger with other data sets).

Figure 11 shows a time series of horizontal sections of TREC vectors at $z = 2.5$ km MSL (the ground elevation varies from 1.5 to 1.9 km) superimposed on the radar reflectivity (shading), and the corresponding streamline analysis. The data were collected by CP-3 on 17 July during CINDE on a day when the Denver Cyclone was evident in the surface mesonet.

At 1405 the TREC vectors and streamlines show a mesoscale cyclonic circulation centered nearly on CP-3. The stronger ambient southeasterly flow can be seen east of about $x = 40$ km with the weaker flow of the vortex to the west in the lee of the Palmer Ridge (compare Fig. 11 with Fig. 3). Numerical model simulations have indicated that the Denver Cyclone results from the interaction of the ambient southerly flow with the Palmer Ridge and Rocky Mountains (Benjamin et al. 1986; Wilczak 1987). At the time shown the main convergence line was oriented north–south and centered near $x = 40$ km. A diffuse line of weak reflectivity can be seen near the convergence line.

From 1405 to 1540 the convergence line moved westward about 10 km and a closed vortex was no longer as well defined. The reflectivity line also moved westward and became more distinct. During this time the southeast flow remained nearly steady, but the southwest flow strengthened. By 1613 the southwest flow had strengthened even more. About this time the first echoes were observed from clouds forming along the convergence line, as documented by Wilson et al. (1988), and by 1650 55 dBZ echoes were observed just above the surface. It seems plausible that the strengthening of the southwest flow may have triggered or enhanced the convection.

Figure 12 shows data from another Denver Cyclone case observed on 24 July 1987. Here TREC is compared to wind measurements obtained from dual-Doppler analysis, surface mesonet, and aircraft. The Doppler winds were synthesized from the CP-3 and Massachusetts Institute of Technology Lincoln Labs FL-2 radars and were heavily filtered leaving only scales comparable to those resolved by TREC. The mesonet data were averaged over a 5-minute period and interpolated to a regular grid following the method of Barnes (1964). The NCAR King Air instrumented aircraft
made several passes across the convergence line flying overlapping box patterns. The data shown represent a 20-minute sample and were interpolated to a Cartesian grid using procedures described by Fankhauser et al. (1985). A more detailed description of this data set can be found in Fankhauser and Rodi (1989).

Although differences in the details of the airflows can be noted, most of the gross features are quite similar. For example, the TREC, dual-Doppler, aircraft, and mesonet measurements show the convergence line in about the same location and having a similar structure. This agreement is quite gratifying considering the different measuring systems used. Many of the differences between the TREC and dual-Doppler winds are due to ground clutter contamination of the CP-3 measurements (the FL-2 radar had ground clutter filters). The thresholding techniques used in TREC eliminated most of the ground clutter contamination and the resulting data holes filled in using CEDRIC.

These comparisons show that TREC is able to de-
This page contains a discussion on airflow determination, particularly focusing on TREC (Traffic Engineering Radar) vectors. The text explains the use of TREC in analyzing airflow, noting its ability to provide boundary-layer airflow over larger areas compared to other methods. It also highlights the importance of Doppler velocity data and the determination of echo patterns.

### 5. Discussion

Building on the TREC cross-correlation analysis technique, the text describes a method for determining airflow in the boundary layer using clear-air return from a single Doppler radar. TREC, used in conjunction with Doppler velocity measurements, helps track airflow patterns accurately, as illustrated in the diagrams and figures provided. These figures show time series of CAPPI's for 17 July 1987 CINDE data at z = 2.5 km MSL, with TREC vectors superimposed on radar reflectivity (left panels) and streamline analysis (right panels). The 5, 10, and 15 dBZ levels of reflectivity are shaded, and the MDT times are indicated in the upper right.

Important considerations include the accuracy of Doppler velocity data and the movement of echo patterns. In certain situations, such as with sheared flow, the pattern motions may not represent the airflow. Evaluation of the method requires comparing Doppler radial velocity measurements with the radial component of the TREC vectors. Any significant differences lead to the discard of the TREC vector.
former produced results in much better agreement with the airflow than the latter. Tracking precipitation echoes resulted in vectors considerably different from the Doppler measurements.

TREC is very sensitive to ground clutter. Ground targets produce strongly correlating features superimposed on clear air echoes; in the cases presented, the latter decorrelated to about 0.5 in 5 minutes. Even small isolated ground targets resulted in vectors of zero magnitude. Although many of the vectors affected by ground clutter could be rejected by thresholding on a high value of $R_{\text{max}}$, prevention in the first place would be more desirable. That is, if TREC were to be used routinely it would be better to consider careful radar site selection or to implement a clutter cancellation algorithm in the processor, rather than trying to correct for clutter after the fact.

TREC can be applied to either conventional or Doppler radar data. In fact, the capability of making Doppler measurements does not offer major advantages for TREC, though it is of modest value. As an example, of the 293 vectors that were discarded by various thresholding methods in the 2 July case, only 19% were rejected using the $\delta V$ threshold, the only threshold that requires Doppler measurements (recall from the discussion in section 3 that using the low $R_{\text{max}}$ and
FIG. 12. Wind vectors determined from (a) TREC (60 × 60 km grid), (b) dual-Doppler analysis using CP-3 and FL-2 data, (c) surface mesonet, (d) NCAR King Air aircraft and (e) TREC (90 × 90 km grid). Data were collected on 24 July 1987 at about 1325 MDT. The TREC, Doppler and aircraft measurements are at z = 2.0 km MSL. The area of dual-Doppler coverage is outlined by solid lines and the positions of CP-3 and FL-2 denoted by ⊙ and □ on (e).
high $\sigma^2$ thresholds produce nearly the same results; hence the removal of noisy vectors could be done using $R_{\text{max}}$ alone if Doppler measurements are not available). A comparison of Figs. 7 and 9 shows the effect of a $\delta V$ threshold. A number of clearly erroneous vectors are eliminated by using this threshold, but filtering algorithms could also be employed for this purpose if necessary. Rather, the need for Doppler radar is better justified by its great value in diagnosing smaller scale phenomena not captured by TREC, and in the study of the kinematics of precipitating systems, both in the single- and multiple-Doppler context.

For optimum use, TREC should be employed with a radar that can routinely detect clear-air echoes out to ranges of 50 to 100 km or farther and has minimal ground clutter contamination. Although we have only presented results from tracking reflectivity patterns in this study, TREC could be applied to Doppler velocity patterns as well, as previously mentioned. Smythe and Zrnić (1983) considered both reflectivity and velocity in their study and found better correlations and agreement with dual-Doppler wind fields when tracking velocity patterns. We applied TREC to velocity data in a few cases and found the opposite to be true. It appeared that the velocity patterns decorrelated faster than the reflectivity patterns, leading to poorer estimates of pattern translation, though we have not explored the matter in detail.

Several potential uses of TREC are apparent. As was demonstrated, TREC results can be interpolated to a Cartesian grid, making it suitable for studying the structure and evolution of the large scale boundary layer airflow. TREC could be integrated with data from other measuring systems to investigate the role of convergence lines in convective initiation. It is well known that many convergence lines initiate convection, while others do not; perhaps TREC can help in discovering why. TREC could also be used to verify results from numerical simulations of the boundary layer such as those of Benjamin et al. (1986) and Wilczak (1987).

In operational modes TREC could be used to obtain near real-time airflow information. This would be particularly useful in short-range forecasting situations and in providing guidance for the operation of field programs. In aviation, wind shifts could be forecasted with better accuracy, resulting in more efficient direction of air traffic in and around airports. On a broader scale TREC could be implemented as part of NEXRAD with the potential of providing mesoscale airflow information over large parts of the United States. On the NCAR CRAY-XMP computer, the computation of the 2 July vectors shown in Fig. 4a took 82 seconds of CPU time. The data consisted of 768 range gates and about 400 azimuths spaced 150 m and 0.9° apart, respectively. Obviously if it took 82 s on a CRAY computer, doing the calculations on a minicomputer would take several minutes. Work is currently underway to implement TREC on the NCAR Alliant FX/4 minicomputer as part of an effort to develop a nowcasting workstation (Lutz et al. 1989). Using the 2 July dataset on the Alliant, TREC took 230 s of CPU time or about three times longer than on the CRAY. This time is not considered excessive, given the scales of motions being determined, but there are several ways that the CPU time could be reduced. One way would be by simply degrading the input data resolution, hence reducing the number of calculations involved. This idea was applied to the 2 July dataset, where the range gate resolution was increasingly degraded to see the effects on the quality of the vectors and the CPU time required. Computer runs were made using every second, third, fifth and sixth range gate (effective range gate resolutions of 300, 450, 750, and 900 m). The corresponding CRAY CPU times were 41, 29, 13 and 10 seconds, a significant decrease from the 82 s for the full resolution run. The quality of the vectors did not show a significant decrease until the 900 m resolution was reached, and even then a vast majority of the vectors looked reasonable. At lower data resolutions the quality of the results could of course be improved by increasing the array size. Note that NEXRAD will have 900 m gate spacing.

Another approach would be to run TREC on Cartesian data. This would have the advantage of not only requiring less CPU time (again fewer data points would be involved in the calculations), but also of performing the correlation analysis on true horizontal planes. A test of this was done by running TREC on a Cartesian dataset (17 July CINDE data) produced by the SPRINT interpolator (Miller et al. 1986). A 100 km × 100 km area of data with 0.5 km resolution required only about 3 seconds of CPU time and the results looked quite similar to Fig. 11. If the radar processor had a hardware interpolator for rapid Cartesian translation, then this approach would be highly feasible for operational use.

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