Near-surface thunderstorm outflow characteristics observed by the TTUKa mobile Doppler radars

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1. Introduction

Convective outflow comprises many of the extreme wind events in the inland midlatitudes and for several regions is the dominant extreme wind type (Letchford et al. 2002). Despite the importance of thunderstorm outflow in understanding the wind loading on structures, current design standards utilize boundary layer wind profiles which do not account for the unique vertical profiles and turbulence characteristics of convective outflow (ASCE-7-05 2006). One reason for the lack of representation of convective outflow characteristics in design standards is the difficulty in acquiring research grade, full-scale data within rare and transient extreme outflow events, which is limited to fortuitous passages over fixed instrumented towers and prior field campaigns (Orwig and Schroeder 2007; Holmes et al. 2008). Given the difficulty in sampling extreme convective outflow with fixed instrumentation, the growing fleet of mobile Doppler radars represents a potentially valuable source for full-scale convective outflow data to be utilized by the wind engineering community.

This study will assess the ability of the two Texas Tech University Ka-band (TTUKa) mobile Doppler radars (Weiss et al. 2009; Hirth et al. 2012) to remotely sense the turbulence characteristics, given herein by the turbulence intensity, which is the ratio of the standard deviation of the wind speed to the mean wind speed over a given period ($I_u = \sigma_u / \mu$) in two convective outflow events:

i. The passage of a nonsevere mesoscale convective system (MCS) over the Texas Tech Wind Science and Engineering Field Site on 15 June 2012 during the Severe Convective Outflow experiment (SCOUT) (Gunter and Schroeder 2012). The representativeness of TTUKa dual Doppler-derived turbulence intensities in the 15 June case will be assessed by comparing them to UVW anemometry installed on a 200 m instrumented tower located near the 90° beam crossing angle of the TTUKa radars.

ii. A series of four internal rear-flank downdraft (RFD) surges occurring within the 18 May 2010 Dumas, Texas supercell intercepted by the second Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX2). The impact of surface interaction on the evolution of turbulence within the RFD surges and turbulence characteristics unique to RFD outflow will be examined using the TTUKa-derived turbulence intensities.

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2. Methodology

The radial velocity and spectrum width returned by the TTUKa radars are utilized for the calculation of turbulence intensity (Fig. 1). As the spectrum width represents the variance of radial velocities returned by scatterers within a given volume and the radial velocity the mean of those returns, they are suitable for the calculation of turbulence intensity. However, as turbulence intensity is typically calculated using the standard deviation of the lateral and longitudinal turbulent components of the wind and the mean wind speed, manipulation of the returned TTUKa radial velocity and spectrum width is required to produce a turbulence intensity estimate comparable to those measured by anemometers. The mean wind speed is calculated through objective analysis and dual-Doppler synthesis of radial velocity plan-position indicator (PPI) scans collected at a single elevation angle, providing the two dimensional wind vectors for each grid space (Fig. 2). In order to use spectrum width as an estimate of the variance of the wind the turbulent contribution to the spectrum width has to be separated from competing effects. The returned spectrum width to a Doppler radar is impacted by several phenomena besides the turbulent variation of the radial wind within each gate (Doviak and Zrnic 1993):

$$\sigma_v^2 = \sigma_s^2 + \sigma_\alpha^2 + \sigma_d^2 + \sigma_o^2 + \sigma_t^2 \quad (1)$$

where σ_v^2 represents the returned spectrum width and the terms on the right-hand side of the equation represent contributions by the wind shear, antenna rotation, differences in hydrometeor fall speed, changes in hydrometeor orientation and turbulence to the total spectrum width. The contributions of antenna rotation, hydrometeor fall speed and hydrometeor orientation to spectrum width may be neglected for low elevation angles and slowly scanning antennas (Brewster and Zrnic 1986; Istok and Doviak 1986). The turbulent contribution to spectrum width can then be retrieved by subtracting an estimation of the spectrum width due to wind shear from the total. The horizontal wind shear is estimated for each grid space in objectively analyzed radial velocity data using centered finite differencing. The vertical wind shear is estimated for the 15 June case by applying a linear interpolation of the 200 m instrumented tower vertical wind profile to the dual-Doppler domain and calculating the vertical wind shear across each radar gate. No method for the estimation of vertical wind shear is available for the 18 May case, however, it is noted that the vertical wind shear contribution to spectrum width in the 15 June case is typically much smaller than the contribution of the horizontal wind shear and that TTUKa-derived turbulence intensities in the 18 May case are smaller than those found in past thunderstorm outflow events, suggesting that neglecting the contribution of the vertical wind shear to spectrum width is not significantly influencing the results. Once the turbulent component of spectrum width has been retrieved, the turbulence intensity is calculated for components of the wind radial to TTUKa-1 and TTUKa-2 as:

$$I_{Ka} = \frac{\sigma_t}{\mu_{Ka}} \quad (2)$$

where I_{Ka} represents the TTUKa-derived turbulence intensity and μ_{Ka} is the dual-Doppler synthesis of TTUKa data at a given grid point.

Prior to the calculation of turbulence intensity, TTUKa data are manually edited to remove regions of aliasing, ground clutter, speckling and incoherency. Data are then objectively analyzed to a Cartesian grid with 25 m grid spacing according to the method outlined by Majcen et al. (2008) using a first-pass smoothing parameter (κ) of 0.013(0.005) for the 15 June(18 May) case calculated according the to coarsest available gate spacing in the dual-Doppler domain. Both radial velocity and spectrum width sweeps are objectively analyzed. It is noted that objectively analyzing the spectrum width will introduce unwanted smoothing to the TTUKa-derived turbulence intensities (Fig. 3). This objective analysis is currently employed to facilitate the calculation of turbulence intensity by having spectrum widths and dual-Doppler syntheses interpolated to the same grid. However, future work will reinterpolate the two dimensional dual-Doppler winds to the original radar coordinates, allowing TTUKa-derived turbulence intensities to utilize the unsmoothed spectrum width data.

For the 15 June case, turbulence intensities are calculated from UVW anemometer data collected by the 200 m instrumented tower. The data are collected at ten vertical levels, including at approximately 74 m above ground level (AGL), which is similar to the center-beam height of 1° TTUKa scans at the location of the tower (Fig. 2), allowing tower turbulence intensities to be compared to TTUKa-derived turbulence intensities immediately upstream of the tower (Figs. 2a, 3). In order for the values to be compared the turbulent component of the 74 m tower wind is split into components radial to the location of TTUKa-1 and TTUKa-2 rather than the lateral and longitudinal components of the wind. A 20 s moving average is applied to 50 Hz UVW observations from the tower to calculate the mean and standard deviation of the wind. The averaging period is shorter than in past studies, however, it is the longest averaging period that results in a mean turbulent component of nearly zero, as recommended by Holmes et al. (2008) and UVW turbulence intensities are similar to those calculated with different averaging periods.

3. Results

a. 15 June 2012 Reese Center, Texas MCS

The MCS crossing the Wind Science and Engineering field site on 15 June produced an extended period of nearly 90 minutes of northwersterly outflow winds. Wind speeds during this period varied between approximately 12 and 25 m s^{-1} in 74 m UVW anemometer data, however, rapid, large fluctuations in the wind speed were not observed and the wind direction remained nearly constant. During the outflow event the TTUKa radars collected 28 dual-Doppler PPI sweeps[1] from which turbulence intensities were calculated for regions of the dual-Doppler domain where the center-beam height difference between the two radars was less than 25 m (Fig. 2). As would be expected in mature thunderstorm outflow,

[1]The primary TTUKa scanning strategy during the event was the collection of dual-Doppler RHI scans immediately downstream of the tower (Gunter and Schroeder 2012).

the wind speed generally increases and turbulence intensity decreases with increasing height AGL.

TTUKa-derived turbulence intensities within a 150 x 400 m rectangle upstream of the 200 m tower generally compare well with UVW turbulence intensities at 74 m (Fig. 3). However, it is apparent that TTUKa turbulence intensities vary less than those calculated from UVW data and are typically lower(higher) during periods of relatively large(small) UVW turbulence intensity. This is likely a result of objectively analyzing the spectrum width returns, which will result in the smoothing of small-scale variations of the turbulence intensity. Differences between the UVW- and TTUKa-derived turbulence intensities can also be attributed to temporal differences between the TTUKa-1 and TTUKa-2 PPIs used in the dual-Doppler synthesis (Fig. 1). The two radars became unsynched shortly after the passage of the initial gust front and exhibit an offset between 30 and 60 seconds throughout the deployment, though this effect is likely mitigated by the relative homogeneity of the outflow, it will damp small-scale variations in the dual-Doppler syntheses, which will then carry over to the calculated turbulence intensities. The TTUKa-derived turbulence intensities in Fig. 3 have been plotted as a box and whisker of each grid point in the 150 x 400 m rectangle in order to assess their variation. Generally, the box and whisker plots exhibit greater variation during periods of larger fluctuation in UVW turbulence intensity, which suggests some small-scale variability in turbulence intensity is being captured by the radars.

b. 18 May 2010 Dumas, Texas Supercell

Dual-Doppler TTUKa data were collected during the passage of the low-level mesocyclone of the Dumas supercell and reveal the evolution of four internal RFD momentum surges which at times exhibited wind speeds greater than 40 m s^{-1} (Skinner et al. 2012) (Figs. 4, 5). The turbulence intensities within the surges are very low, typically less than 0.06 and in some regions below 0.02, which is far below values expected in synoptic-scale high wind events and below values found in past observations of rear-flank downdrafts (Holmes et al. 2008). The low turbulence intensities may in part be attributed to the sampling of RFD surge winds near the time they first impact the surface. It can be seen that turbulence intensities are at a minimum when RFD surges are first captured by the dual-Doppler synthesis and increase with time as the surge wraps cyclonically around the near-surface circulation (Fig. 4). This increase in turbulence intensity with time is due to both deceleration of the mean wind speed and an increase in spectrum width, which is consistent with the mechanical generation of turbulent eddies as air parcels within the RFD surges interact with the surface. However, the turbulence intensities within “mature” RFD surges which have been present in the dual-Doppler syntheses for nearly three minutes remain below values found in past experiments despite ample time to adjust to the surface roughness. Several additional factors may contribute to these low turbulence intensities, including variation in the center-beam height of the TTUKa-2 data[2], which varies between approximately 15 and 25 m AGL across the dual-Doppler domain. Though turbulence intensity is expected to decrease with height and these center-beam heights are further aloft than heights at which turbulence intensity is typically considered for wind engineering (10 m AGL) it is difficult to quantify the representative height of TTUKa spectrum widths due to the volumetric sample provided by the Doppler radar, which will include returns from very near the surface as well as further aloft. Additionally, the small resolution volumes achieved by the TTUKa radars will fail to represent turbulent eddies greater than the resolution volume in the spectrum width. Turbulent eddies larger than TTUKa bins will be represented as horizontal wind shear across the grid space being considered and removed in the calculation of the turbulence intensity, likely resulting in TTUKa-derived turbulence intensities lower than what would be measured from an anemometer. A low bias to TTUKa-derived turbulence intensities may also be introduced due to the mass of the hydrometeors from which the spectrum width values are derived. As hydrometeors will be imperfect tracers of turbulent motion, the spectrum width will likely slightly underestimate the turbulent component of the wind within each resolution volume (Brewster and Zrnic 1986).

4. Summary and Future Work

Turbulence intensities have been calculated from dual-Doppler synthesized wind speed and objectively analyzed spectrum width for two convective outflow events sampled by the TTUKa mobile Doppler radars. Comparison of TTUKa-derived turbulence intensities to those measured by UVW anemometry at a similar height and location in nonsevere MCS outflow reveal that turbulence intensities derived from volumetric radar dara are similar to those from point data anemometer data (Fig. 3). Radar-derived turbulence intensities within a succession of

[2]Turbulence intensities derived from TTUKa-1 spectrum width are similar to those from TTUKa-2

internal RFD momentum surges are small compared to values from prior events. This is in part due to the sampling of "immature" outflow shortly after it has impacted the surface and turbulence intensities within RFD surges increase with time and may additionally be influenced by turbulent eddy sized larger than the resolution volume of TTUKa data and the use of hydrometeors as tracers of turbulent motion.

For turbulence intensities derived from Doppler radar PPI scans to be of the most use to the wind engineering community, efforts should be made to collect synchronized dual-Doppler data very near the surface and with radial components to each radar from regions with beam crossing angles near 90° nearly representing the lateral and longitudinal components of the flow. Additionally, interpolation of dual-Doppler synthesized winds to native radar coordinates would allow unsmoothed spectrum widths to be used in the calculation of turbulence intensity and result in more accurate values.

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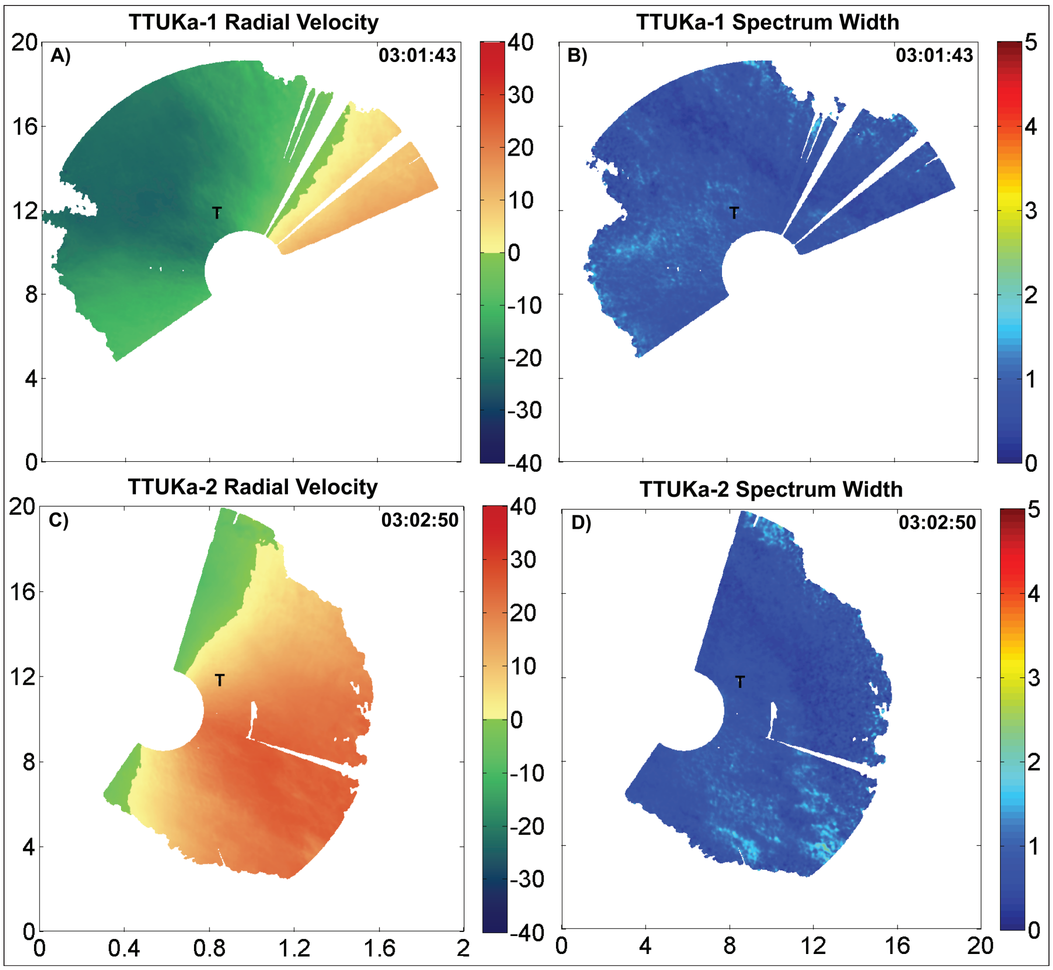

Fig. 1. Objectively analyzed TTUKa radial velocity (m s^{-1}) (A, C) and spectrum width (m s^{-1}) (B, D) 1.0° elevation angle PPIs from 15 June 2012. Bold "T" represents location of the 200 m instrumented tower.

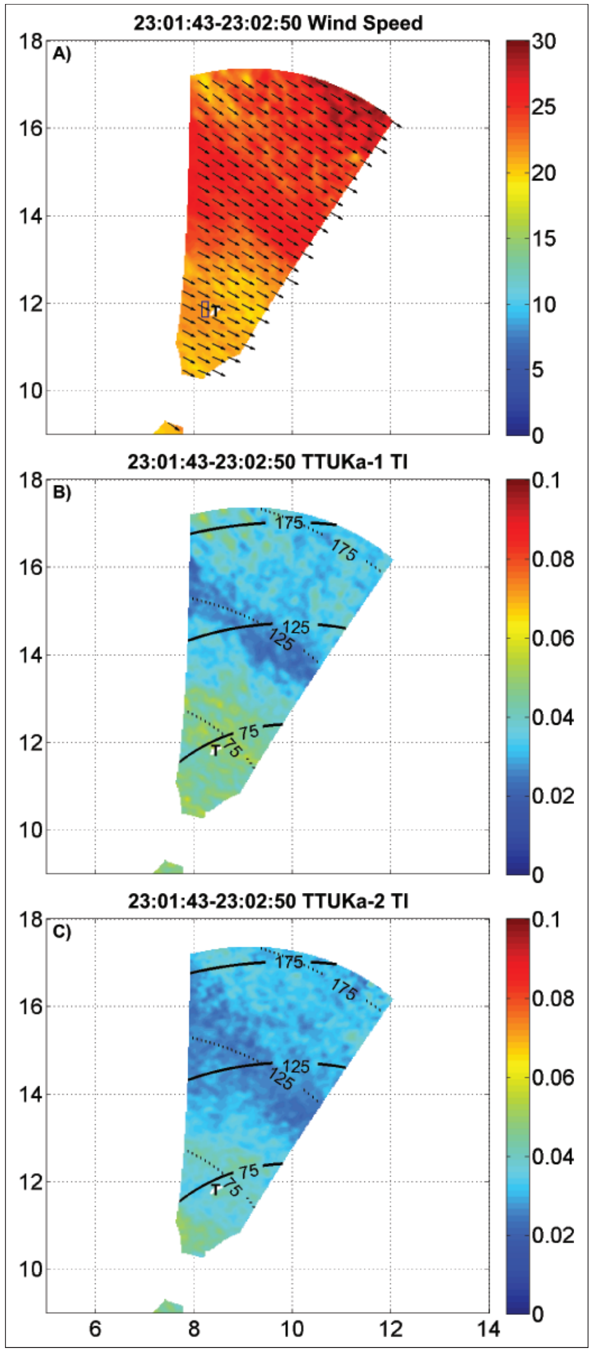

Fig. 2. (A) Dual-Doppler synthesis of radial velocity scans in Fig. 1, (B) TTUKa-1 derived turbulence intensities and (C) TTUKa-2 derived turbulence intensities. Thin rectangle, solid(dashed) contours and T denote region used for 200m tower comparison in Fig. 3, center beam height of TTUKa-1(TTUKa-2) and location of 200 m instrumented tower.

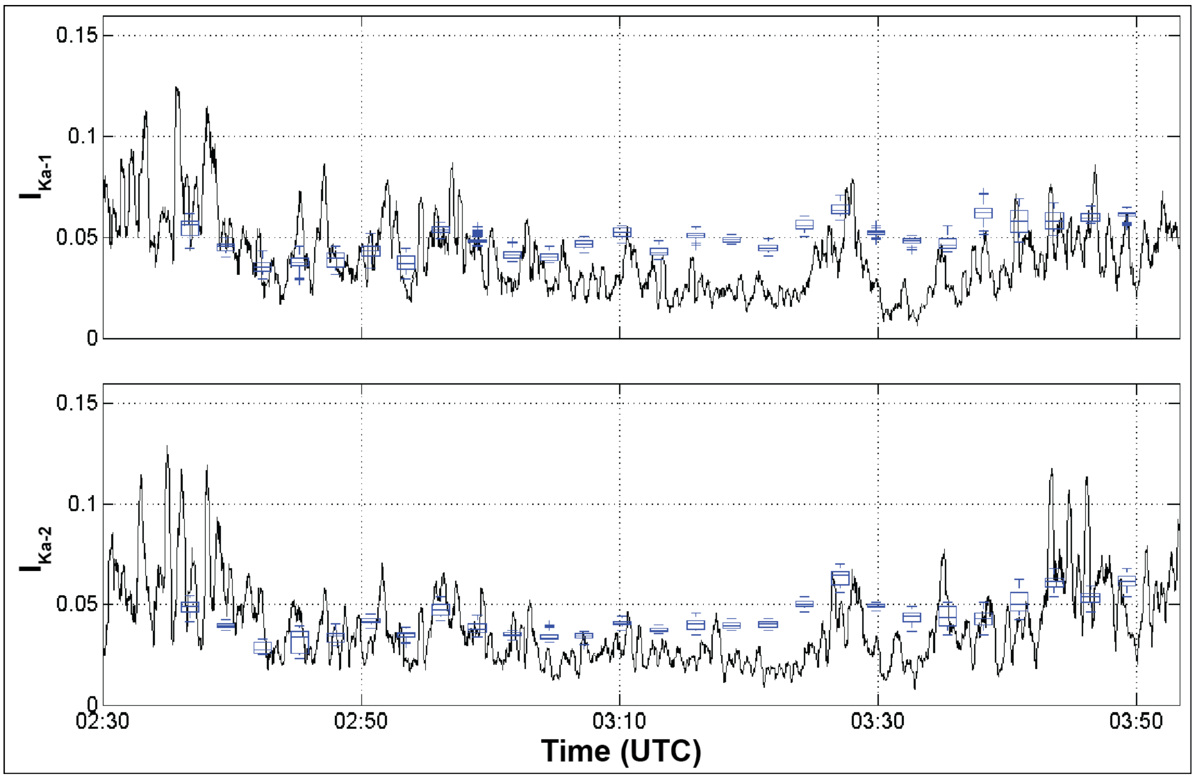

Fig. 3. (top) Time series of 74 m tower UVW turbulence intensity of the TTUKa-1 radial component of the wind with box and whisker plots of TTUKa-1 derived turbulence intensities within a 150 x 400 m rectangle upstream of the tower (Fig. 2a). (bottom) As in the top panel but for the TTUKa-2 radial component of the wind.

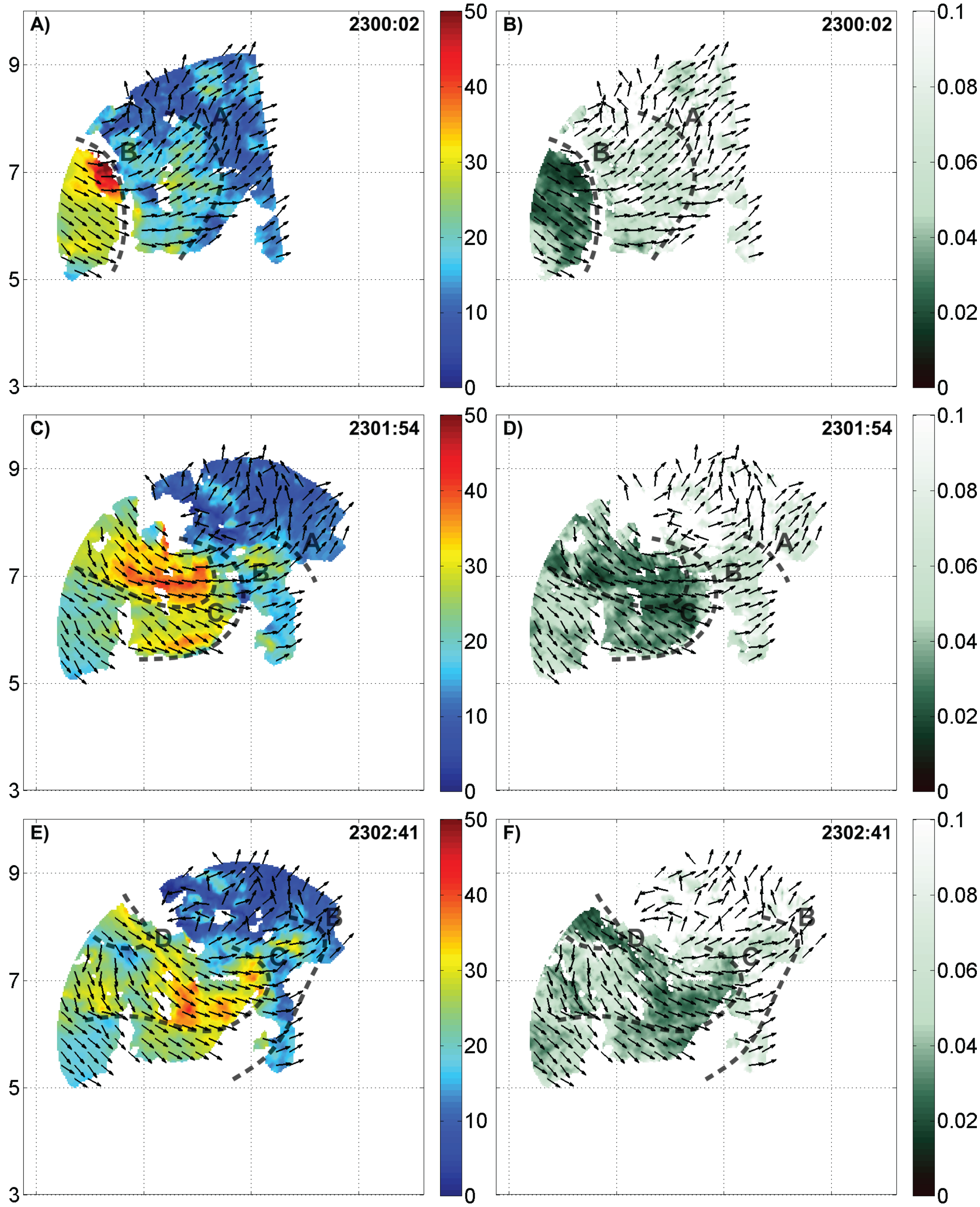

FIG. 4.

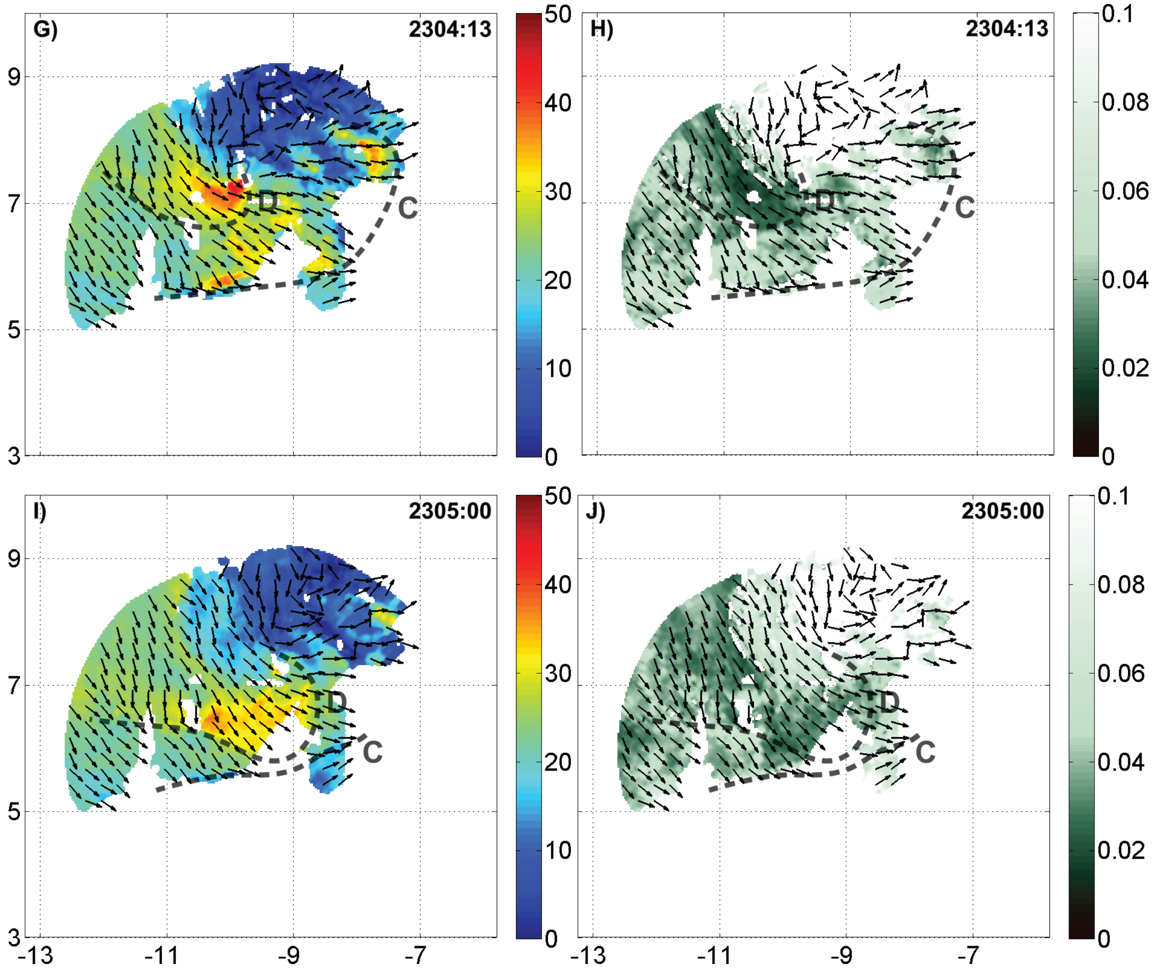

Fig. 5. (Continued from Fig. 4) (A, C, E, G, I) TTUKa dual-Doppler syntheses of the 18 May 2010 Dumas, TX supercell. (B, D, F, H, J) Corresponding TTUKa-2 derived turbulence intensities. Dashed lines indicate subjectively analyzed position of internal RFD surge gust fronts.

FIG. 6. Photograph looking north towards the Dumas supercell taken during the TTUKa dual-Doppler deployment from a location south of TTUKa-2 by the Lyndon State College and National Center for Atmospheric Research photogrammetry team A. Estimated position of internal RFD surge gust fronts are labeled with dashed lines and "V" denotes a wall cloud associated with a brief, intense circulation north of the apex of surge D.