Comparison of In-Situ Pressure and DOW Doppler Winds in a Tornado and RHI Vertical Slices through 4 Tornadoes during 1996-2004

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1. Introduction to Part A

Conditions inside tornadoes are difficult to observe directly due to the transience, relative rarity, size, and violence of the phenomena.

Accurate climatologies of the core flow diameter of tornadoes, and actual core-flow swaths (as distinguished from damage swaths), are lacking. However, a rough estimate is that approximately 600 tornadoes occur in the midwestern United States each year (about 1/2 of the total in the United States), over an area of approximately 1.5 x 10^6 km^2. Very approximately, the swath over which the core flow of an average tornado passes can be calculated by assuming a 100 m diameter and a 10 km length, resulting in a swath extending over 1 km^2. Therefore, approximately 600 km^2 out of 1.5 x 10^6 km^2 of the midwest is impacted by core flow winds every year. The resultant mean recurrence interval for core flow passage over any particular location is 2500 years. The passage of significant, say 70 ms^{-1} or greater, core flow winds is even rarer, with recurrence intervals of 10,000 years or longer depending on thresholds and assumptions.

Not surprisingly, in-situ observations of tornadoes are rare, and accomplished exclusively, or nearly so, through the use of targeted instrumentation. Winn et al. (1999) described the first in-situ measurements inside a large tornado near Allison, Texas that was rated F4. The F3 damage swath was 1.3 km across. Doppler On Wheels (DOW) data at a range of 9 km showed that the core flow was approximately 800 m with peak winds of about 85 ms^{-1} Winn et al (1999) estimated that their observations might have been within 660 m of the tornado center, but a detailed comparison with DOW data, which might permit accurate navigation of the in situ observations with respect to the core flow, has not, as of yet, been undertaken.

Recently, new technology and techniques have been developed that permit more frequent, though still somewhat rare, in-situ pressure observations within the core flow regions of tornadoes (Samaras and Lee, 2004, this volume). Pressure deficits of 40 hPa and 100 hPa were measured in tornadoes in 2003 and additional observations were obtained in 2004. In one of these cases, DOW high resolution Doppler velocity measurements were available contemporaneously with the passage of the core flow over the instrument, permitting a detailed analysis. Preliminary analyses are presented below.

2. Tornado overview

On 15 May 2003, a tornadic supercell thunderstorm crossed the northern Texas panhandle and produced several tornadoes. Some of these were observed by the DOW radars and one by the in situ instrument.

a. Navigation of DOW data

The DOWs were in motion during much of the lifetime of the tornadoes, but since the topography was very flat, powerlines and other features provided a rich clutter target environment. It was possible to determine the DOW location within 50-100 m during nearly

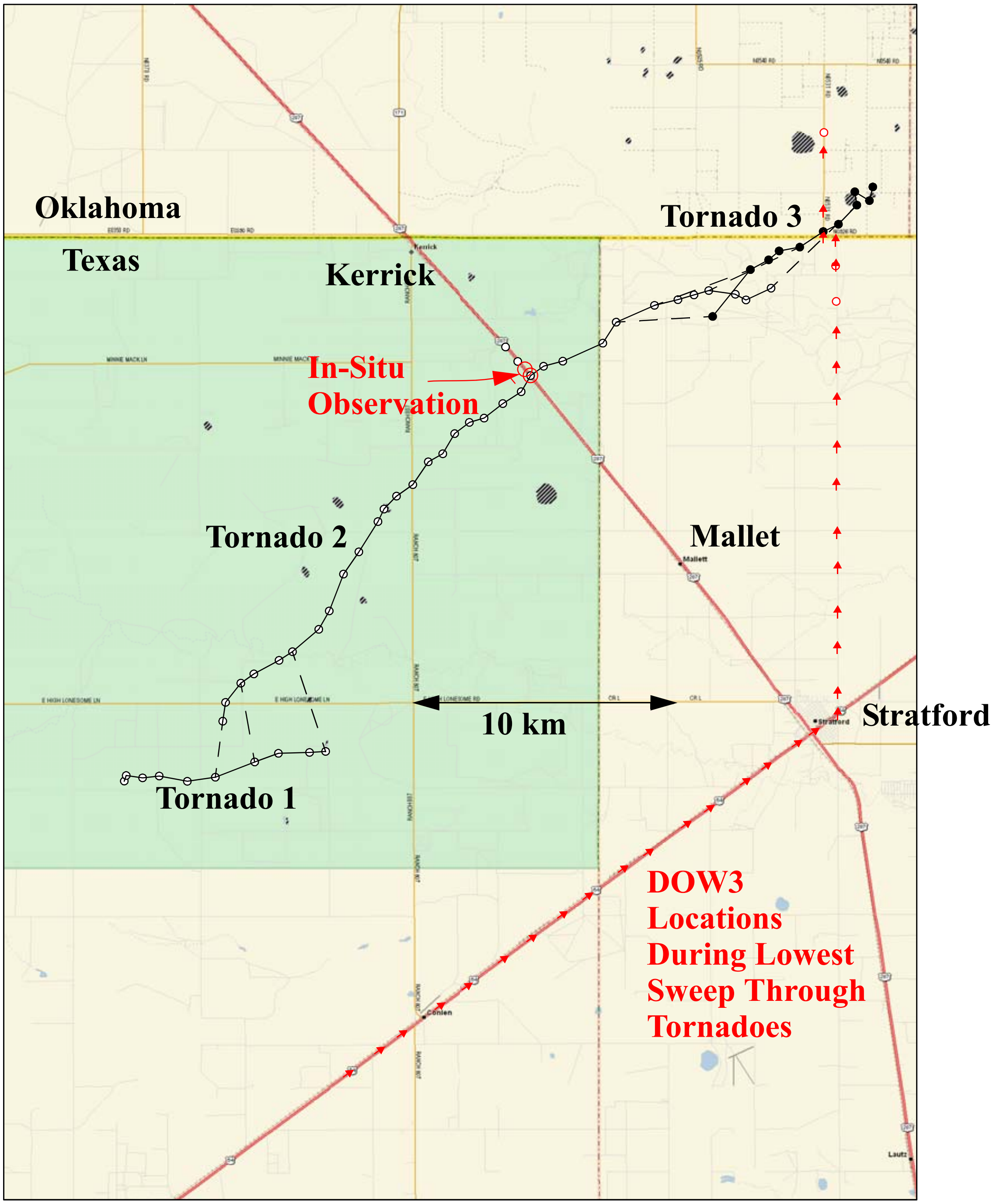

Figure 1: Tracks of three tornadoes observed by DOW near and during the time of the in-situ observation. Tornado 2 crossed the surface probe at the indicated location while the tornado was under continuous observation by the travelling DOW. Red arrows represent DOW locations during lowest elevation sweeps occurring at alternating intervals of 48 s and 63 s. Dashed lines connect selected contemporaneous observations of tornado 1 and tornado 2. Tornado 3 was a weak but large tornado that contained numerous sub-tornado-scale vortices.

every low level scan. Video of the DOW fleet provided further confirmation of DOW locations, and the precise time of road crossings. Using the Doppler velocity of clutter targets and video evidence of road crossings, the location of the DOW could be determined for all low level scans. The orientation of the DOW was measured using the clutter grid to within 1°.

b. Tornado tracks

At lease three separate tornadoes were observed by the DOW surrounding the time of the in situ observations. The DOW conducted near-surface sweeps at alternating intervals of 48 s and 63 s, permitting a detailed retrieval of the history of the track, intensity, core flow diameter, and other parameters of the tornado.The DOW-derived tracks of these tornadoes are illustrated in Figure 1. These longer track tornadoes rotated cyclonically, though there were shorter lived tornado-

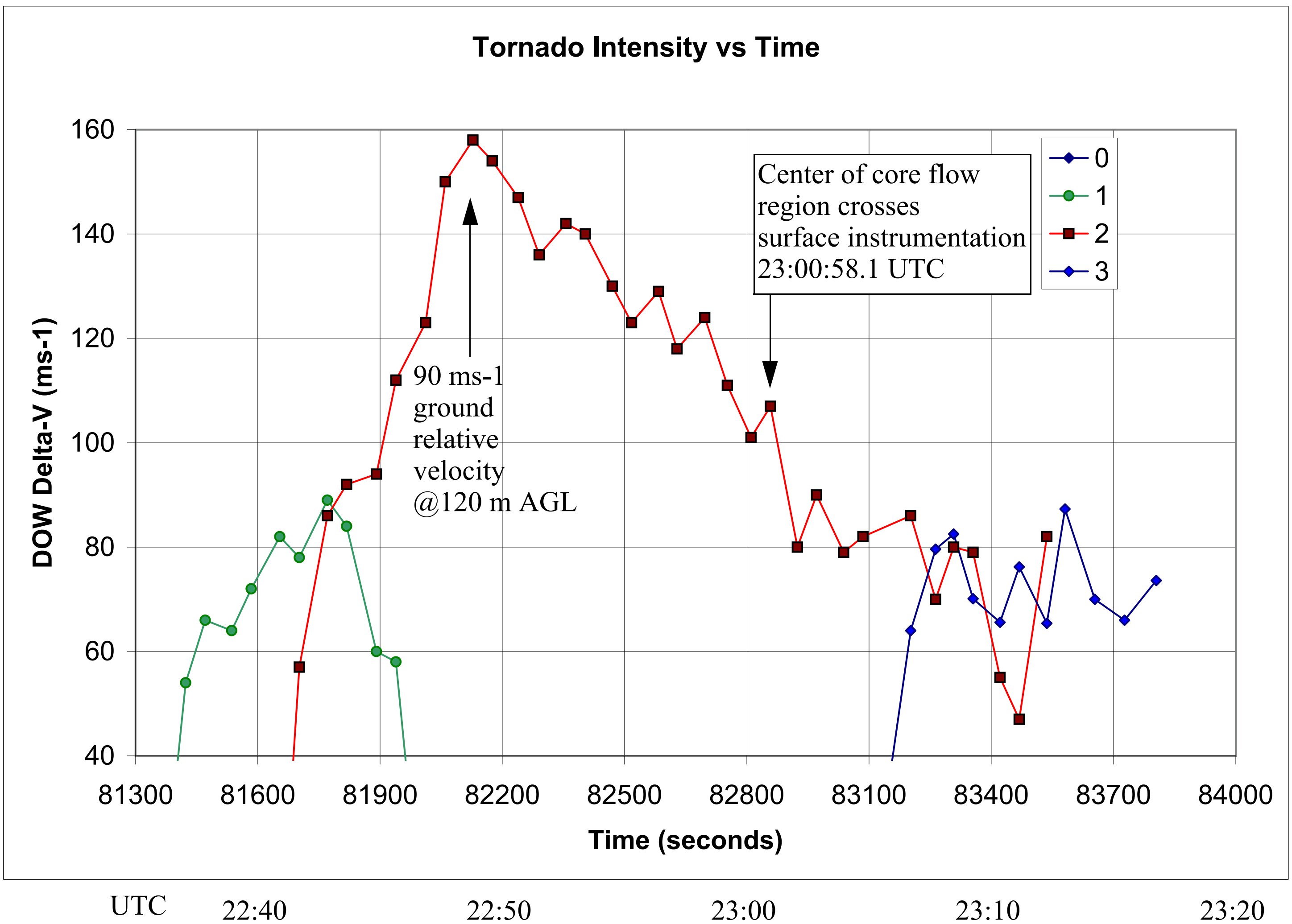

Figure 2: Time history of tornado intensity, as manifested by the difference in Doppler velocities measured across the core flow region of each tornado. The time of the in situ observation in Tornado #2 is demarked.

strength circulations that rotated anticyclonically. The time history of the intensity of these tornadoes, as indicated by the difference in Doppler velocities across the core flow region, is illustrated in Figure 2. (A short lived tornado, #0, occurred before the plotted period.) Tornado #1 reached moderate intensity then dissipated as Tornado #2 intensified. The location of Tornado #1 suggested that it was not associated classically with the mesocyclone and that the #1-#2 transition was not a classic cyclic genesis. Tornado #2 reached a peak intensity of nearly 160 ms^{-1} delta-V with peak ground relative velocities on the south (right) side of the core flow near 90 ms^{-1} at approximately 22:49 UTC, at 120 m AGL, then weakened considerably as it tracked northeastward across the surface instrumentation. The center of the core flow region of the tornado crossed the instrumentation at 23:00:58.1 +/- 1.0 seconds UTC. The tornado proceeded northeastward, then dissipated as the large but weak Tornado #3 formed. After Tornado #3 became less distinct, a strong rear flank downdraft, with Doppler velocities up to 63 ms^{-1} at 50 m

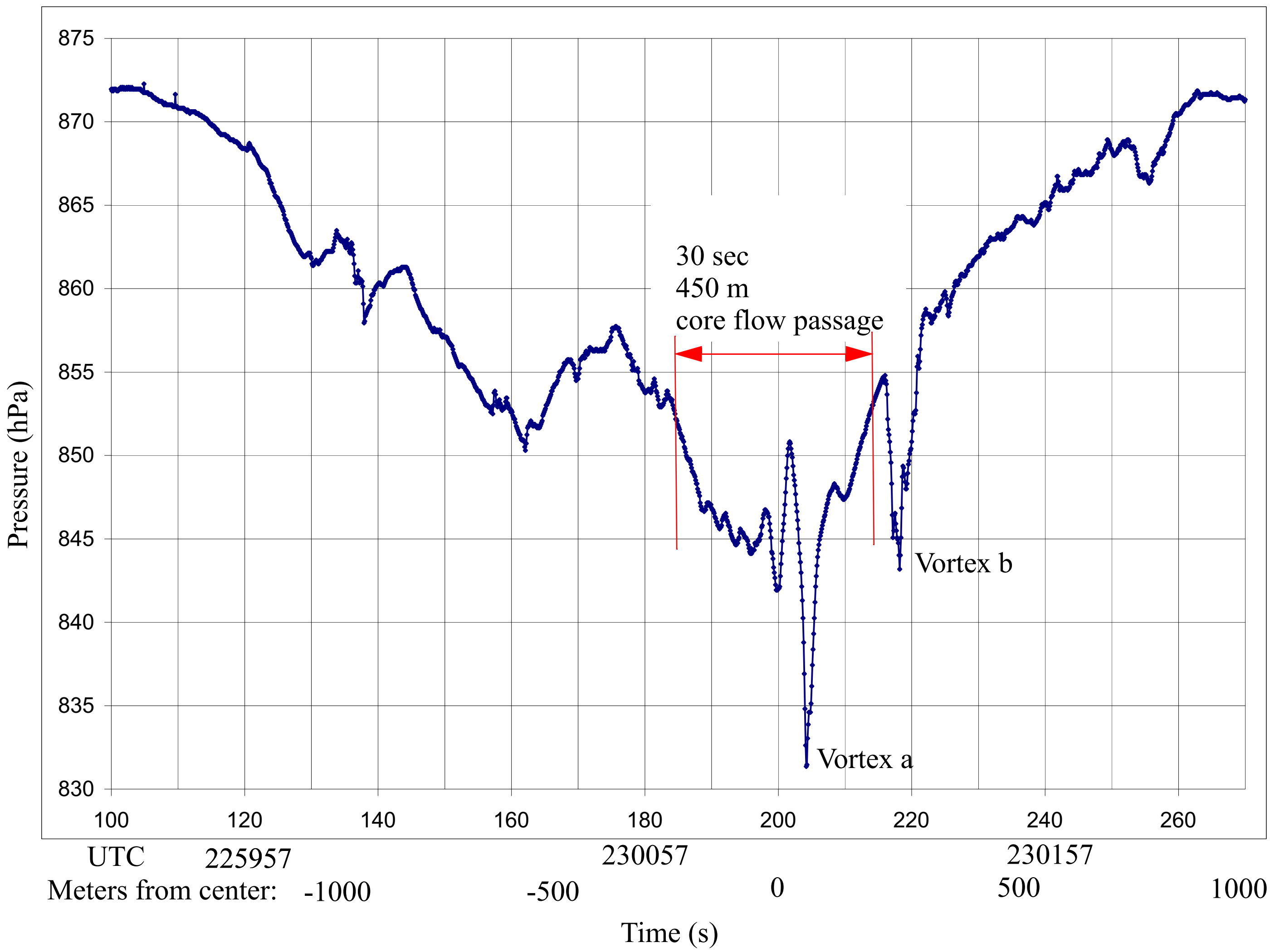

Figure 3: Time history of pressure measured at in situ probe during the passage of the tornado. The core flow region, as measured by the DOW radar, crossed the probe during the indicated period. Individual short-duration downward spikes in pressure were likely associated with weak sub-tornado-scale vortices which were evident in video, but not resolved by the DOW. Times recorded by the in situ probe deviated slightly from DOW times. Probe times are used in the discussion of the analysis for simplicity. Multiple vortices a and b are labelled.

agl, developed, and at least one additional tornado, not tracked precisely by the DOWs, was observed.

3. In-situ observations

A deployable in-situ probe was deployed next to a roadway northwest of Stratford, Texas, ahead of Tornado #2 (see Fig. 1). The tornado, manifested visibly as a large bowl-shaped lowering with considerable surrounding rain and embedded small condensation funnels, crossed the roadway and the probe at approximately 23:01 UTC.

Probe instrumentation is described in detail elsewhere (see Samaras and Lee, 2004, this volume). Pressure measurements at intervals of 0.1 s were obtained and are plotted in Figure 3. All times are seconds after 22:57:57, the nominal start time of probe recording. Pressure drops from approximately 872 hPa at T=100 s to an extreme minimum of 832 hPa at T=204 s, then recovers to 872 hPa by T=265 s. Excluding two downward spikes in the pressure, lasting for less than 10 s each, the minimum pressure was approximately 842 hPa at approximately T=200 s (23:01:15 UTC). This is very near to, but not precisely, the probe crossing time indicated by the DOW data (23:00:58 UTC).

4. Comparisons between in-situ and DOW observations.

a. Basic Core Flow

The existence of DOW Doppler velocity data over the surface probe at the time of the tornado's passage provided the unique opportunity to compare these diverse measurements. In order to compare two-dimensional radar measurements with stationary zero-dimensional surface data, a space-time correction was conducted, sliding the quasi-steady-state tornado velocity field defined by the DOW over the surface probe. DOW observations permitted the precise measurement of both tornado translational velocity (Figure 4) and core flow diameter. (Figure 5) as the tornado passed over the surface probe. Space-time conversions were

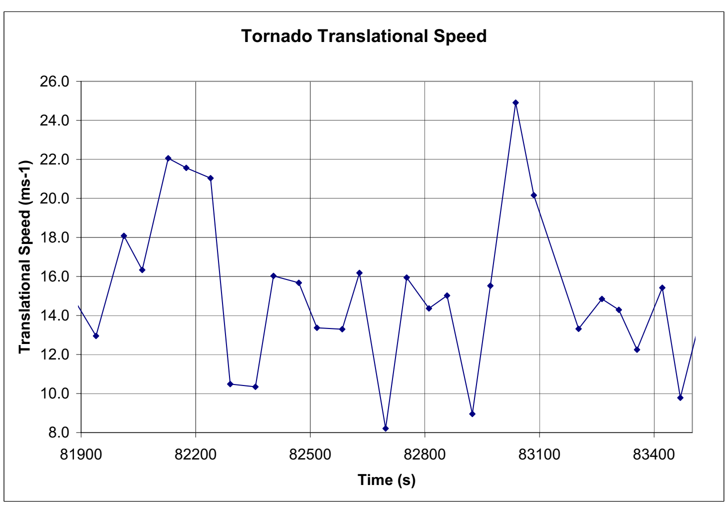

Figure 4: Time history of translational speed of Tornado #2. as determined using DOW-determined tornado centers.

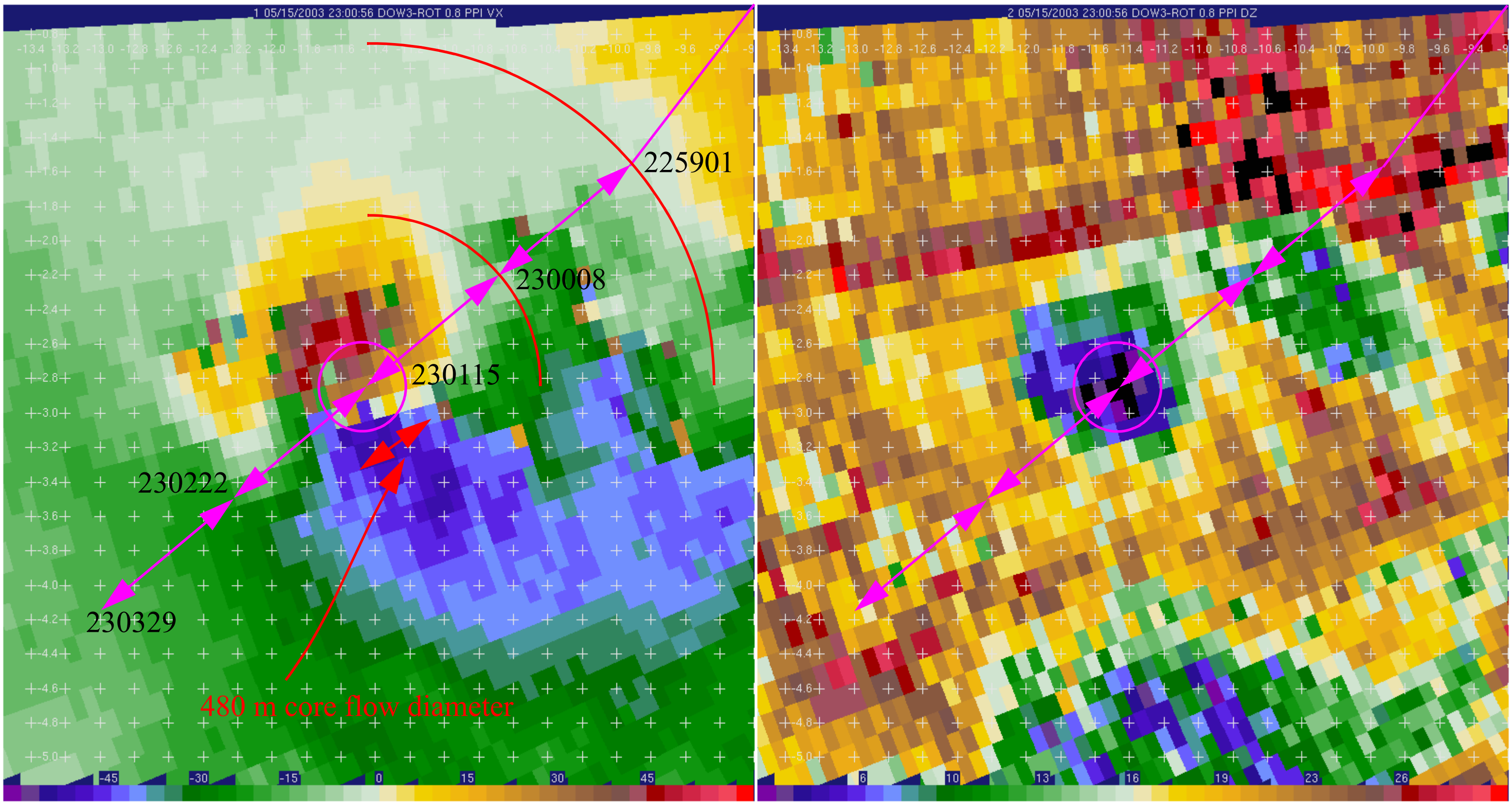

Figure 5: Low level DOW radar sweep over Tornado #2 near the time of the in-situ observation. Right: Doppler velocity showing inbound (blue) and outbound (red) couplet. Core flow diameter of 400 m is outlined in pink. Pink arcs at 1 km and 2 km range and arrows illustrate the results of a space-time conversion and the time of the crossing of different regions of the storm over the in situ probe. Tick marks 200 m.

plotted on the time history of pressure (Figure 3), and on the low level radar sweep (Figure 5). The core flow region crossed the probe in approximately 30 s as illustrated in Figure 3.

Using the pressure history from the in-situ observations and the translational velocity of the tornado obtained from DOW observations, cyclostrophic tangential windspeeds were calculated (Figure 6). This calculation assumed that the pressure measured at the surface could be related to the tangential flow of the tornado above the near-surface corner flow. The precise geometry of the core flow passage over the probe affected the cyclostrophic wind calculation. Since the DOW was in motion and at moderate range to the probe, it was difficult to be definitive concerning this geometry. DOW observations suggested that the center of the core flow region passed south of the probe. However, observers nearer to the probe, including one of

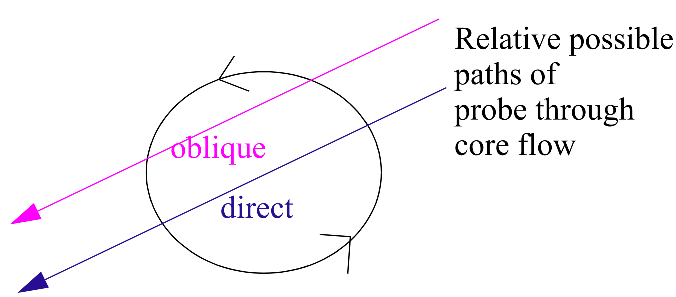

Figure 6: Schematic of a direct and glancing passage of the core flow region over the probe

us (Samaras) believed that the center of the tornado crossed the probe. These two scenarios are illustrated below in Figure 6.

Cyclostrophic wind profiles calculated using the two above scenarios are illustrated in Figure 7. The results are remarkably good and in close agreement with DOW Doppler velocity observations. Peak winds of approximately 40 ms^{-1} are near DOW-estimated tangential flow estimates of 53 ms^{-1} (based on delta-V / 2). Peak cyclostrophic winds occur at just over 200 m distance from the center, very consistent with the 450 m core flow diameter measured by the DOW.

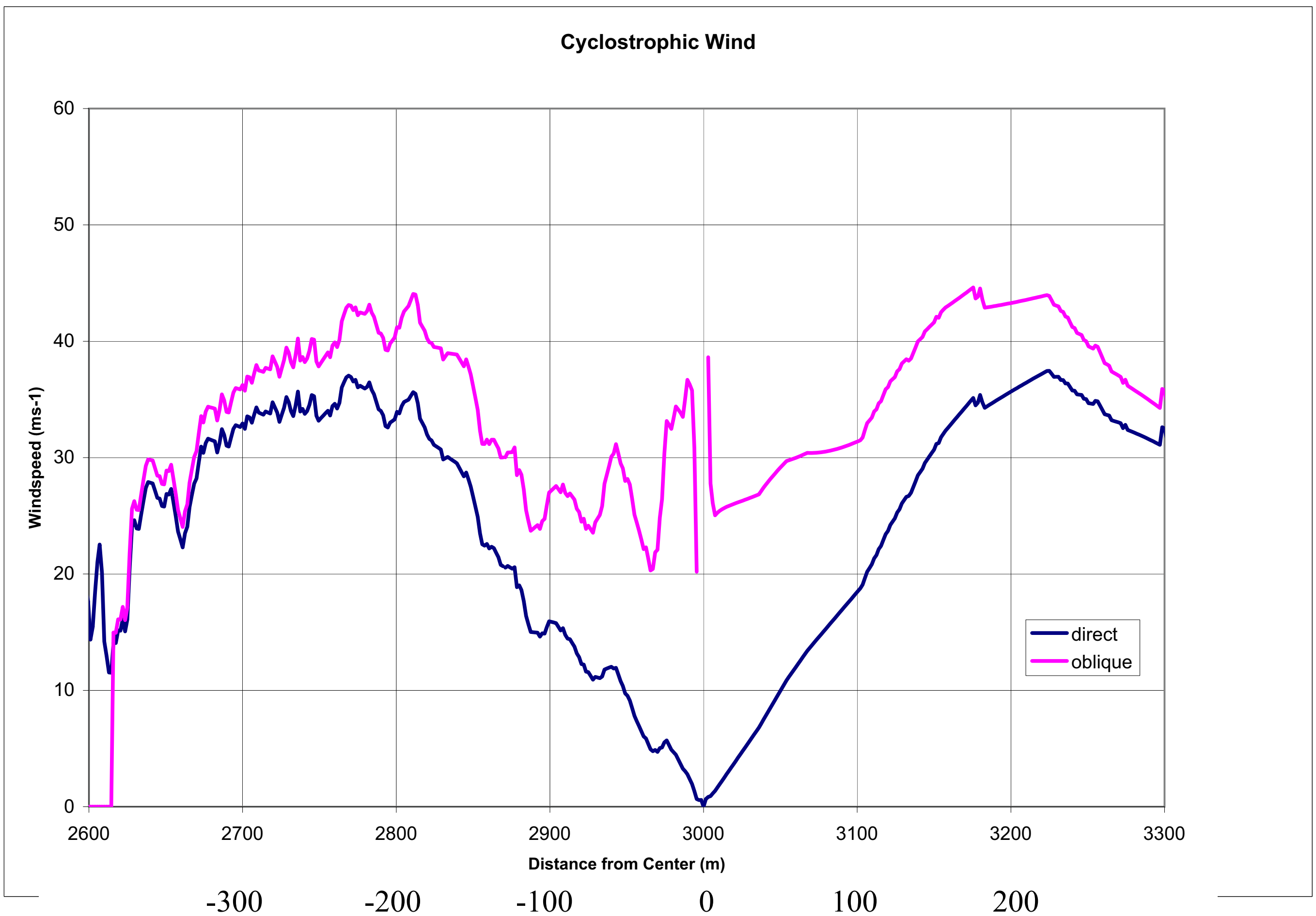

Figure 7: Calculated cyclostrophic tangential winds in Tornado #2 based on in situ pressure observations and DOW translational speed and core flow navigation data. The oblique curve represents a core flow center passing 100 m south of the probe. Since the DOW measured the the core flow diameter at 450 m, the probe would have still experienced a substantial period under the core flow region. An eight second box car average and spike elimination has been conducted on the pressure data to smooth the velocity calculation and eliminate pressure gradient reversals.

b. Sub-vortices and other features

In addition to the one minute scale drop and rise in pressure discussed above, there were other prominent features that could be correlated to structures in and near the tornado.

Well before the tornado core flow passage, at a calculated range of 600 m to the tornado center, a pressure minimum approximately 8 hPa lower than the longer period trendline occurred. The low level DOW radar sweep that most closely correlates with the time of this event occurred at 23:00:08-23:00:12 UTC and is shown in Figure 8. The low reflectivity eye of the tornado had a complex structure with an inward protuberance of high reflectivity 600 m ahead of the path of the tornado and over the in situ probe at this time. The velocity structure in and near the protuberance was not well resolved. Strong inbound Doppler velocities adjacent to outbounds suggested unresolved structures.

During and immediately after the core flow passage, two short duration downward spikes of pressure occurred. The duration of each spike was less than 10 s, suggesting a spatial scale of about 100 m, and the pressure drops were 13 and 15 hPa. One hundred meter scales were not well resolved by the DOW at a range of over 11 km despite short range gates and oversampling (See Wurman and Alexander 2004, this volume). The actual DOW beamwidth at this range was nearly 200 m.

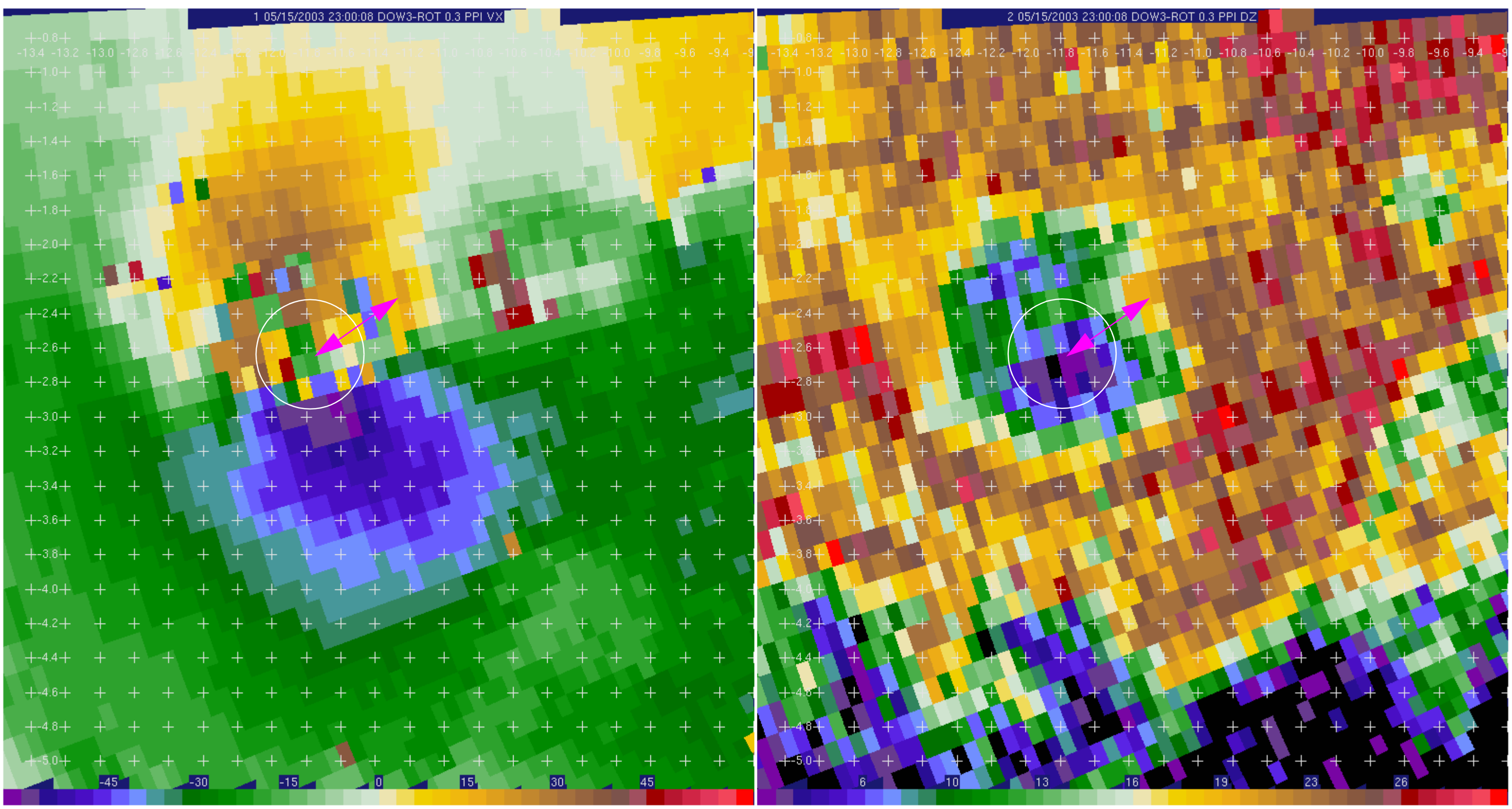

Figure 8. Similar to Figure 5, but from previous low level DOW scan at 23:00:08 UTC. Tick marks are 200 m. Doppler velocity (left) and radar reflectivity (right). Core flow region delineated with white circle diameter 600 m. Reflectivity protuberance and velocity perturbations evident 600 m (40 s) ahead of tornado center as illustrated with pink arrow.

However, visual observations taken near the probe and visual and DOW observations from close range to Tornado #3, which had a similar appearance, revealed that both tornadoes had a multiple-vortex structure.

Using similar methodologies cyclostrophic winds in the multiple vortices could be calculated. The translational speed of the vortices with respect to the parent tornado were not known. Wurman (2002) presented evidence that some multiple vortices moved at roughly 0.5 - 1.0 of the tangential velocity of the tornado, suggesting a speed of approximately 20-40 ms^{-1} in this case. Since it was believed that the probe was impacted by the northern side of the core flow, the translational speed of the tornado and the relative translational speeds of the vortices would subtract, resulting in speeds of approximately 15 m/s from east to west. This was consistent with video evidence of small condensation funnels moving from east to west to the north of the probe. Using the translational value of 15 ms-1 results in the spatial pressure distribution shown in Figure 8 and cyclostrophic tangential wind profile shown in Figure 9 for vortex a and

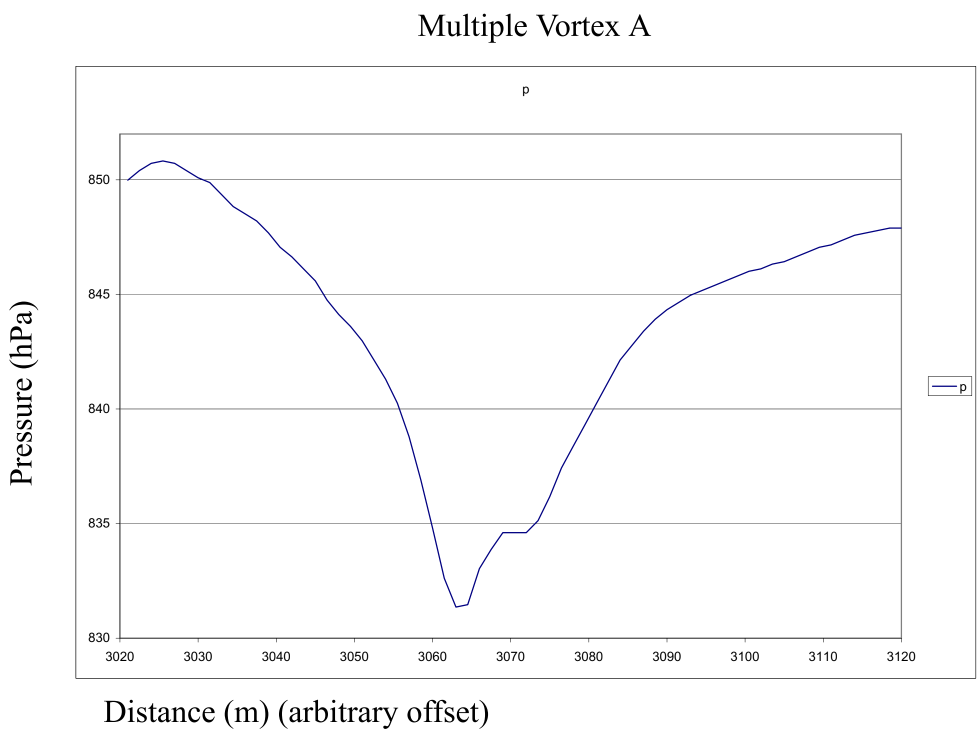

Figure 9: Pressure history in multiple vortex A

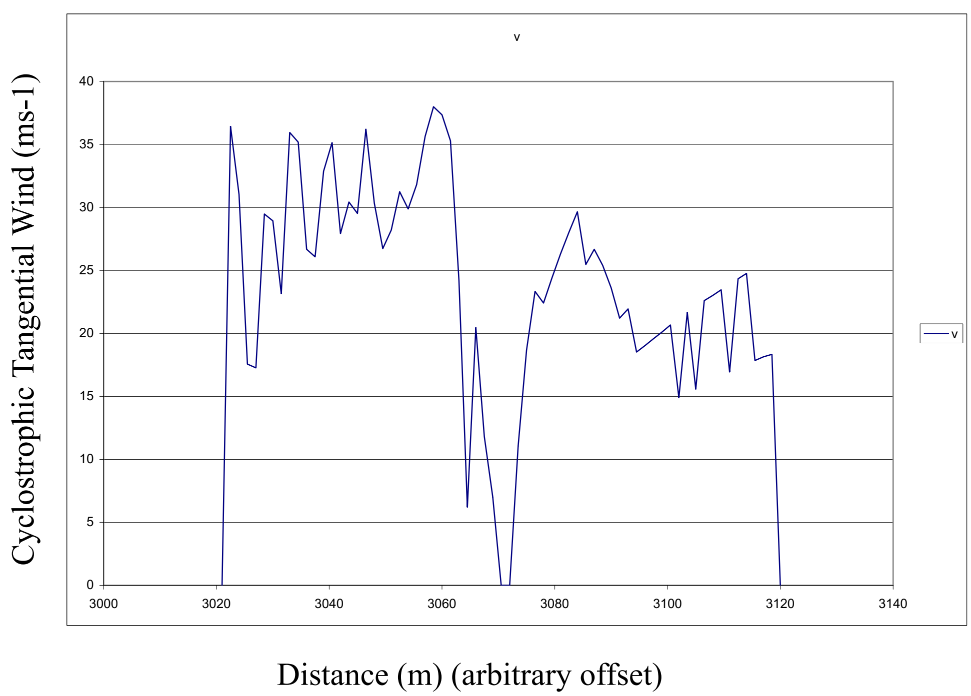

Figure 10: Cyclostrophic winds in multiple vortex a

Figures 10 and 11 for vortex b. Strong gradients in pressure were associated with only moderate cyclostrophic winds due to the small radius of curvature in the vortices. Peak tangential winds in vortex a were near 30 ms^{-1} with values of 40-50 ms^{-1} in vortex b. The latter values were comparable to the tangential velocities of the parent tornado. Smoothing had been applied to the pressure field to remove short period reversals in sign of the pressure gradient.

The possible two-dimensional structure of the multiple vortices was suggested by observations in Tornado #3 taken 13 minutes after the in situ observations. Figures 12-13 showed the complex structure of Tornado #3 which contained several sub-vortices with scales of approximately 100 m (100 m diameter circles delineate some of the vortices in Figure 13.) and delta-v's of approximately 40-70 ms^{-1}, implying tangential velocities of 20-35 ms^{-1}, reasonably consistent with the calculated cyclostrophic winds shown in Figures 9 and 11.

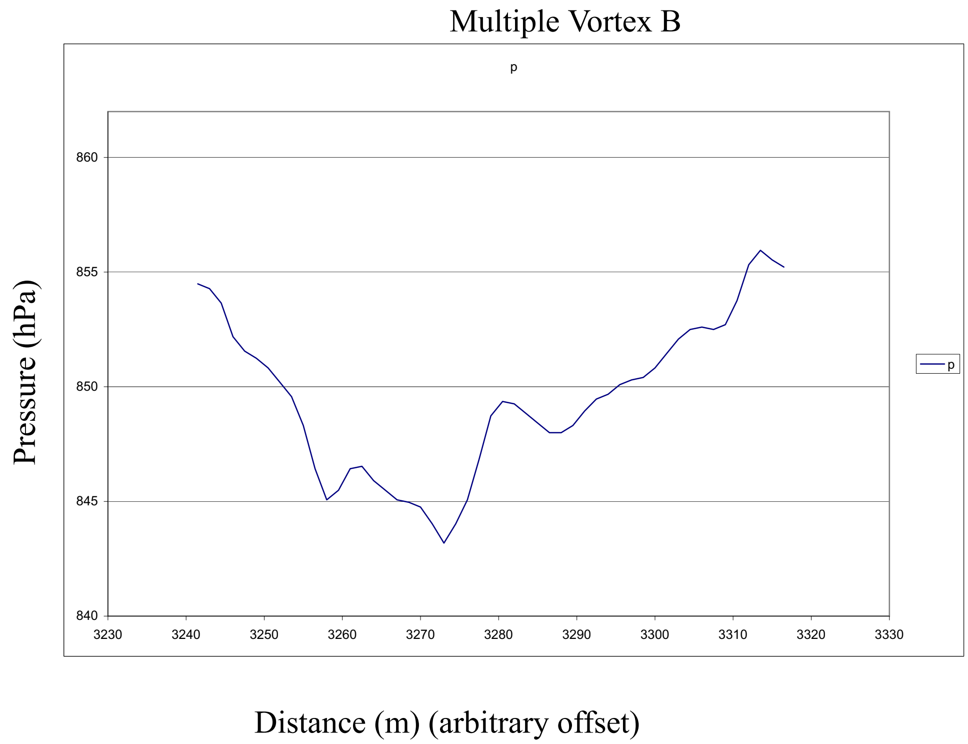

Figure 11: Pressure history in multiple vortex B

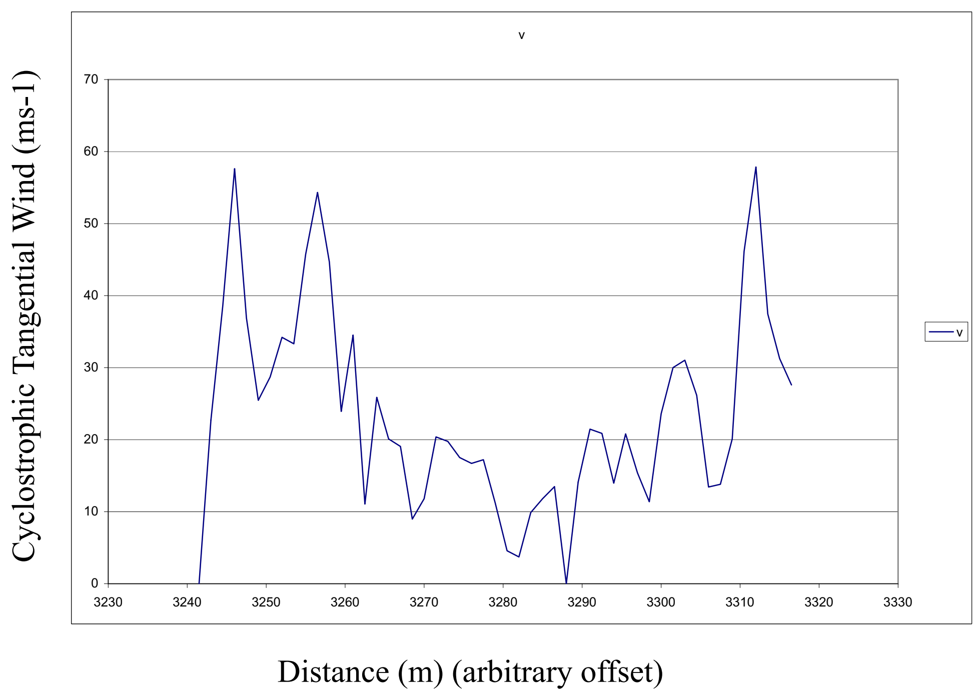

Figure 12: Cyclostrophic winds in multiple vortex B

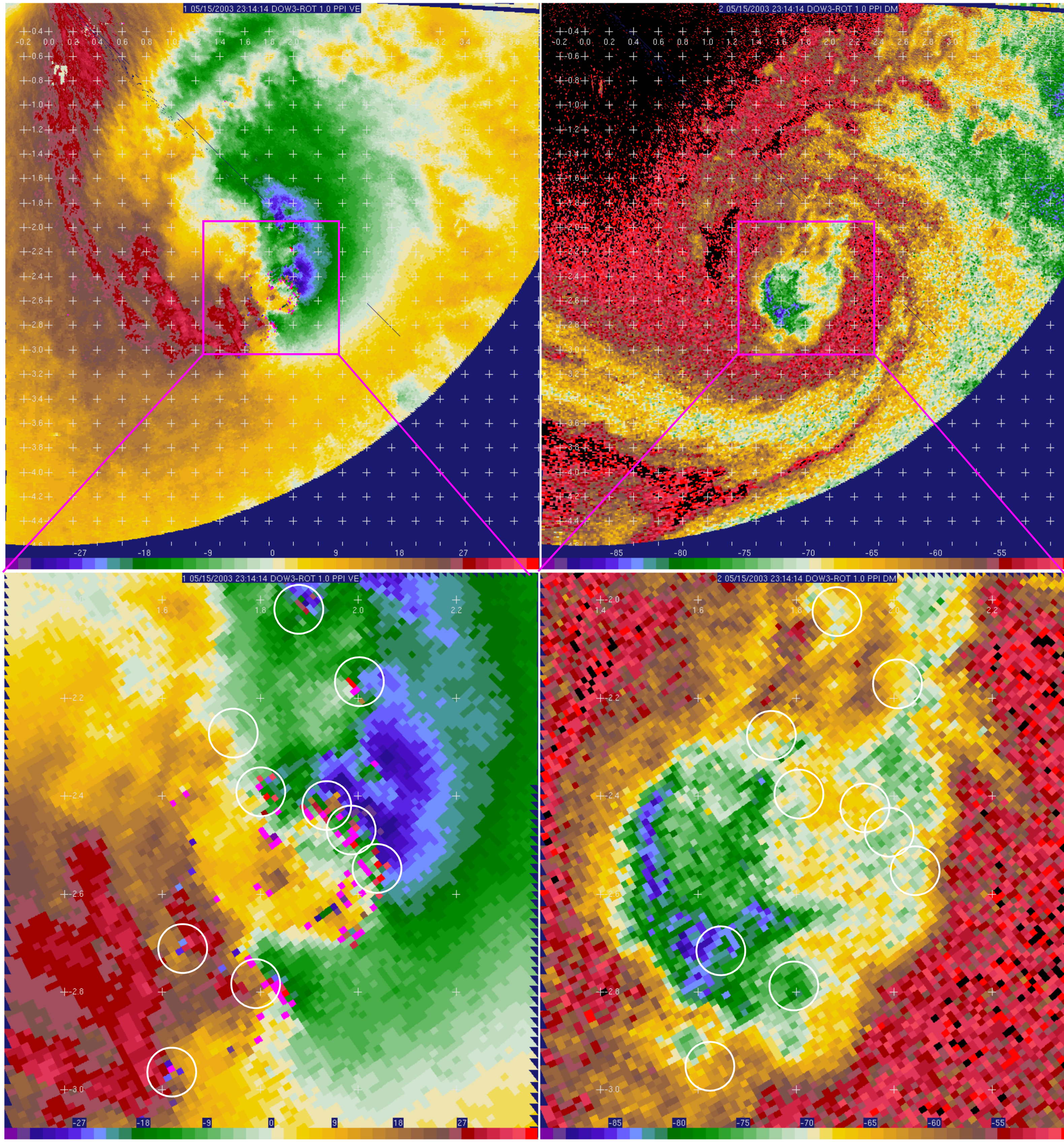

Figure 11 (top) and Figure 12 (bottom). DOW Doppler velocity and reflectivity in Tornado #3.
Several sub-tornado-scale vortices are delineated with 100 m diameter white circles. Tick marks are 200 m.

B. Vertical Slice (RHI) Data in Tornadoes

1. Rolla, Kansas, 30 May 1996

The first vertical RHI-type radar sweeps resolving the core flow of a tornado were collected by the DOW1 radar system in 1996 (Fig 12) on 30 May near Rolla, Kansas. While velocity data collected by the DOW1 near the end of its life were noisy, the vertical structure of the velocity and reflectivity field of the tornado were resolved.

Since the slope of a tornado is not generally in the plane of the RHI scans, and is often not constant in direction or magnitude, RHI slices typically cross through the core flow and eye from one side to the other (Fig. 13), resulting in scans with an unusual appearance. Furthermore, beams that pass directly through the center of the core flow region intersect the highest wind speed portion of the core flow where that flow is nearly perpendicular to the beam, resulting in near-zero Doppler velocity.

Even in the noisy 1996 data, maximum wind speed near the surface, as well as the pseudo-eye surrounding the true eye of the tornado were evident. The true eye of the tornado and inner rings of lofted dust were only barely resolved to radar sensitivity problems.

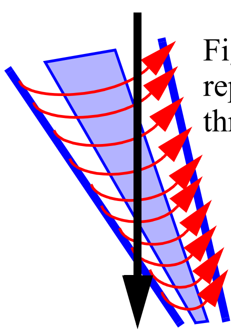

Figure 13: Schematic representation of one RHI slice through tornado core flow

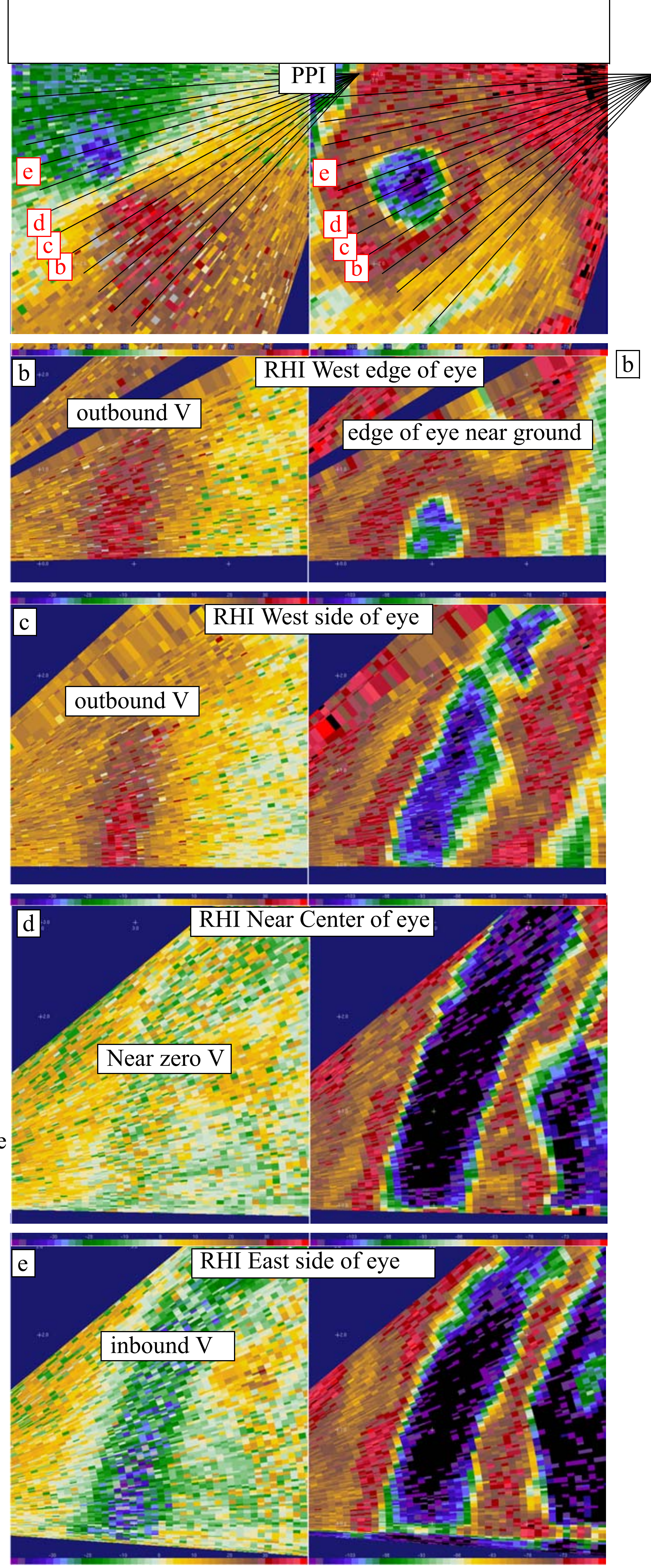

Figure 14: (right) Several RHI slices through the Rolla, Kansas tornado of 30 May 1996. Lines lines on PPI slice show location of RHI slices, of which 4 are shown.

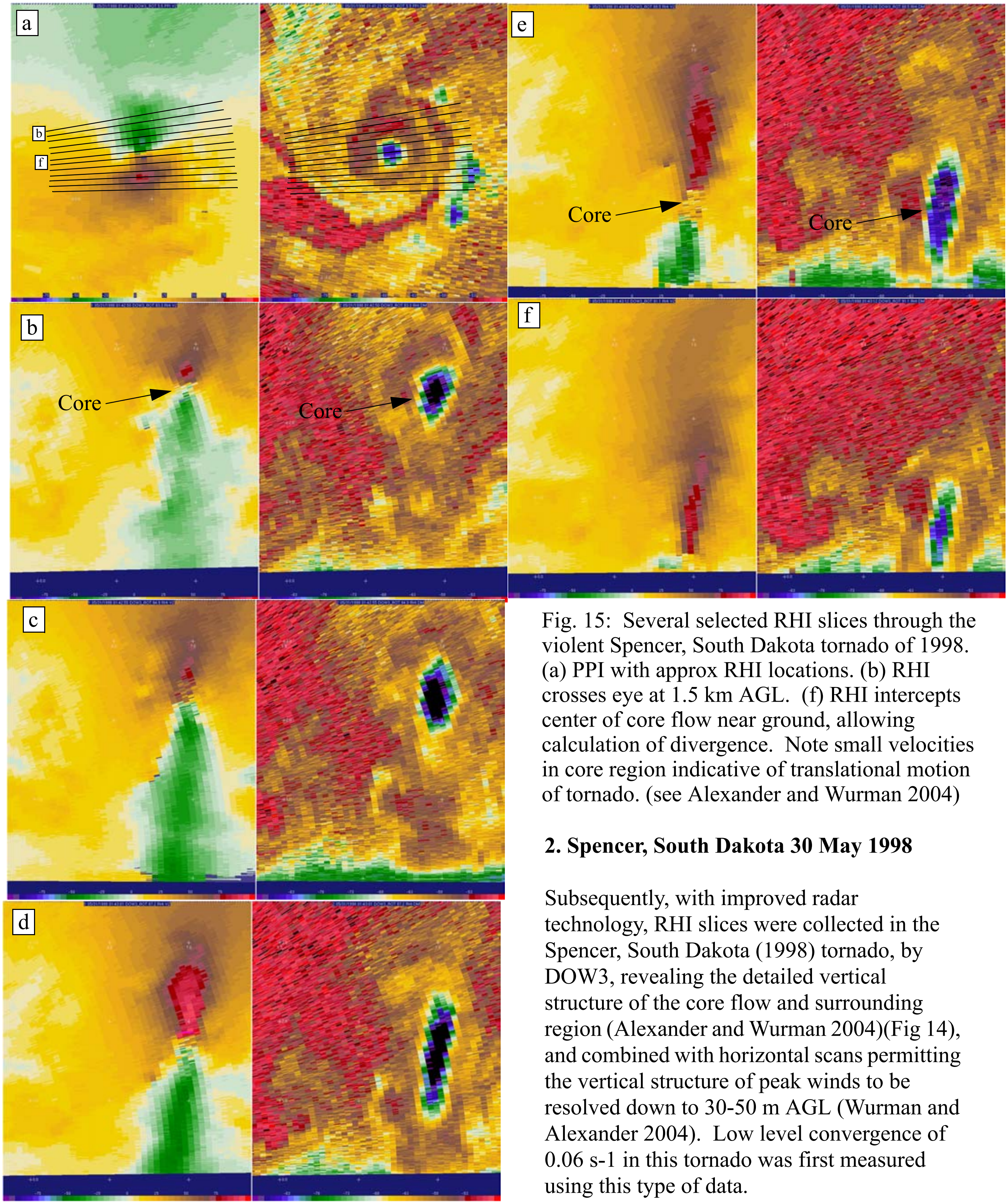

Fig. 15: Several selected RHI slices through the violent Spencer, South Dakota tornado of 1998. (a) PPI with approx RHI locations. (b) RHI crosses eye at 1.5 km AGL. (f) RHI intercepts center of core flow near ground, allowing calculation of divergence. Note small velocities in core region indicative of translational motion of tornado. (see Alexander and Wurman 2004)

2. Spencer, South Dakota 30 May 1998

Subsequently, with improved radar technology, RHI slices were collected in the Spencer, South Dakota (1998) tornado, by DOW3, revealing the detailed vertical structure of the core flow and surrounding region (Alexander and Wurman 2004)(Fig 14), and combined with horizontal scans permitting the vertical structure of peak winds to be resolved down to 30-50 m AGL (Wurman and Alexander 2004). Low level convergence of 0.06 s-1 in this tornado was first measured using this type of data.

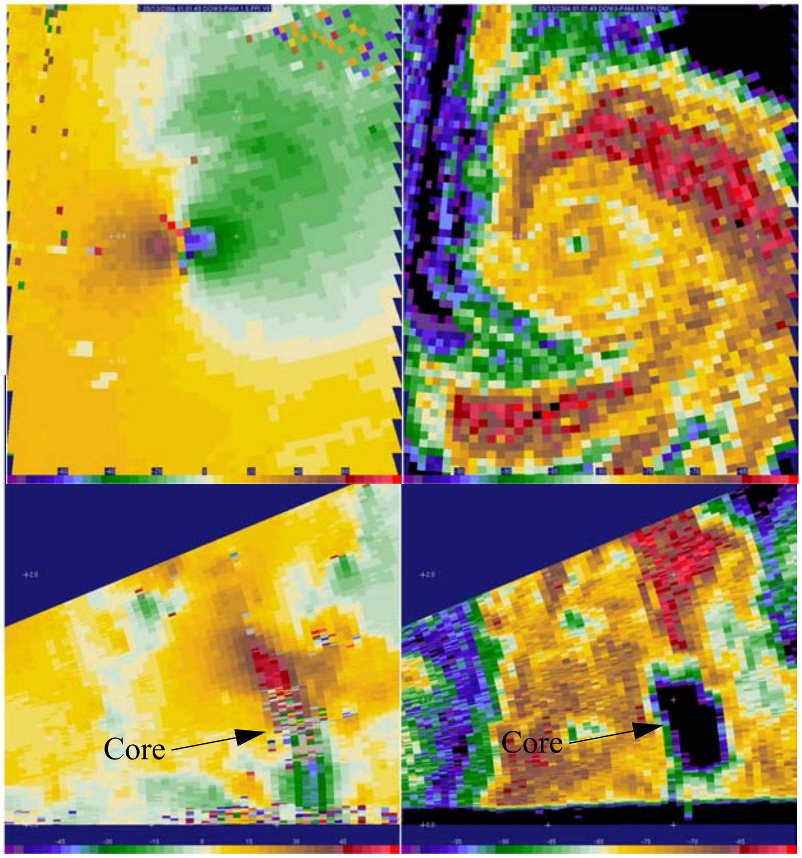

Fig 16: PPI and RHI slices through Attica, Kansas tornado on 12 May 2004. RHI slice intercepts eye in bottom panels

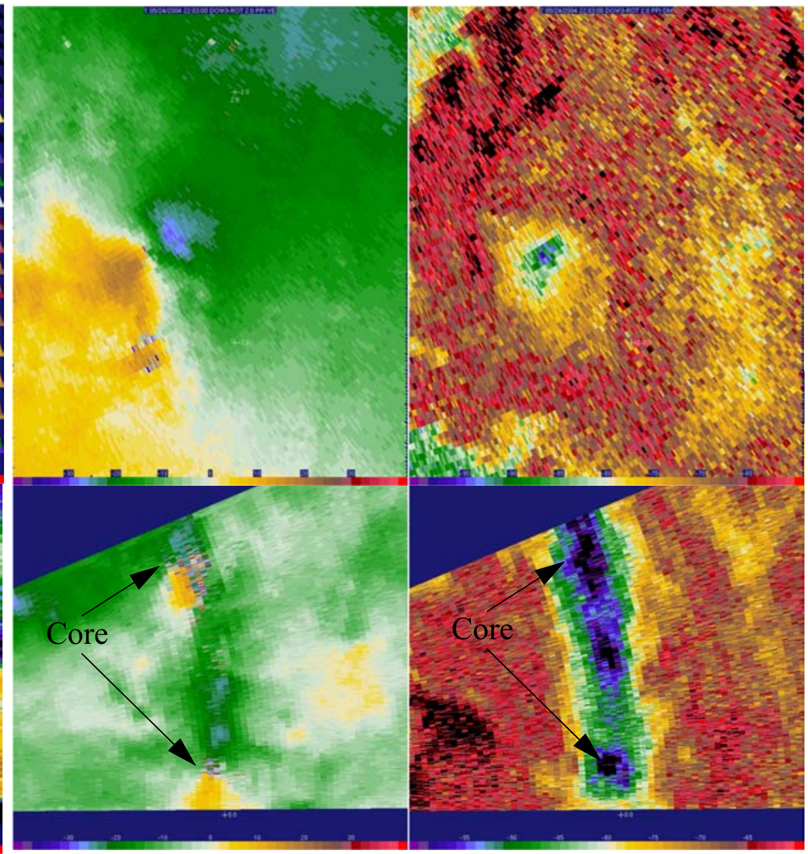

Fig. 18: PPI and RHI slices through dissipating tornado in rope stage in Belleville, Kansas on 24 May 2004. RHI slice intercepts core flow region twice

3. Attica, Kansas 12 May 2004

The DOWs were able to collect vertical structure data using RHI slices in two tornadoes during 2004, retrieving excellent quality velocity and reflectivity data. On 12 May 2004, a tornado passed near Attica, Kansas and a DOW collected several vertical cross-sections through the core flow / eye and surrounding region as shown in Fig 16.

4. Belleville, Kansas 24 May 2004

A DOW collected vertical cross-section RHI data in a dying tornado, in the “rope” stage, in Belleville, Kansas on 24 May 2004. The tornado was highly contorted and this resulted in single RHI sweeps intersecting the core flow region twice, as illustrated schematically in Fig 17, resulting in the very unusual Doppler velocity image shown in Fig 18.

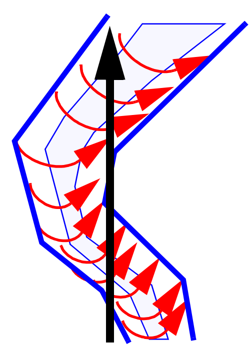

Fig. 17. Schematic representation of RHI slice that crosses core flow region of a roping tornado twice, once near the ground and again aloft. This results in the unusual Doppler image shown in Fig. 18.