

Observations of the Boundary Layer near Tornadoes and in Supercells Using a Mobile, Collocated, Pulsed Doppler Lidar and Radar

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ABSTRACT

During the Second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2), in the spring of 2010, a mobile and pulsed Doppler lidar system [the Truck-Mounted Wind Observing Lidar Facility (TWOLF)] mounted on a truck along with a mobile, phased-array, X-band Doppler radar system [Mobile Weather Radar–2005 X-band, phased array (MWR-05XP)] was used to complement Doppler velocity coverage in clear air near the radar–lidar facility and to provide high-spatial-resolution vertical cross sections of the Doppler wind field in the clear-air boundary layer near and in supercells. It is thought that the magnitude and direction of vertical shear and possibly the orientation and spacing of rolls in the boundary layer have significant effects on both supercell and tornado behavior; MWR-05XP and TWOLF can provide data that can be used to measure vertical shear and detect rolls. However, there are very few detailed, time-dependent and spatially varying observations throughout the depth of the boundary layer of supercells and tornadoes.

This paper discusses lidar and radar data collected in or near six supercells. Features seen by the lidar included gust fronts, horizontal convective rolls, and small-scale vortices. The lidar proved useful at detecting high-spatial-resolution, clear-air returns at close range, where the radar was incapable of doing so, thus providing a more complete picture of the boundary layer environment ahead of supercells. The lidar was especially useful in areas where there was ground-clutter contamination. When there was precipitation and probably insects, and beyond the range of the lidar, where there was no ground-clutter contamination, the radar was the more useful instrument. Suggestions are made for improving the system and its use in studying the tornado boundary layer.

1. Introduction

We have some understanding of the basic dynamics of supercells and the tornadoes they produce based on

Doppler radar observations, numerical simulations, and highly idealized theories (e.g., Bluestein 2013). The character of the boundary layer in supercells, especially underneath low-level mesocyclones and in tornadoes, and in the rear-flank downdraft and inflow regions is critical to our full understanding of tornado dynamics and tornadogenesis (Rotunno 2013). Our current knowledge of the boundary layer is, however, based almost entirely on numerical simulations and theory under highly idealized conditions: there are relatively few detailed observations of the wind field profile at low levels (in the surface boundary layer) in nature (e.g., Wurman et al.

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2013). Although mobile, W-band and X-band radars have probed boundary layer structures in clear air along surface boundaries (e.g., Weiss et al. 2006; Marquis et al. 2007), insects or lofted dust are required for them to be detected. Often the backscattered signal is below the noise level, so the (low level) wind field is therefore not completely sampled or resolved.

In many instances Doppler radar observations are available in the upper portion of the boundary layer (e.g., Bluestein et al. 2007b, their Fig. 15). Either serendipitous surface [e.g., on 24 May 2012 at El Reno, Oklahoma, at a Mesonet site data (Oklahoma Mesonet 2011)], instrumented-tower (Dowell and Bluestein 1997) data, profiler observations (Lehmiller et al. 2001), or targeted measurements made with surface probes or instrumented vehicles (Skinner et al. 2011; Hirth et al. 2008; Karstens et al. 2010; Lee et al. 2011, 2012; Wurman et al. 2013) are used, often to supplement the Doppler radar observations.

To determine what spatial resolution is needed to address problems in supercell and tornado kinematics and dynamics, a brief review of some aspects of supercell and tornado dynamics follows.

a. Supercell dynamics

While it is known from theory, numerical simulations, and observations that the environmental, boundary layer shear (over hundreds of meters in the vertical) can influence supercell behavior (e.g., McCaul and Weisman 2001; Tanamachi et al. 2013b), including the evolution of surface vortices, less is known about the effects of *heterogeneity* in boundary layer shear on the substorm scale (approximately kilometers). In addition, Crook and Weisman (1998) found evidence that weakening of the thermally driven, daytime, convective boundary layer might lessen the disruption of low-level mesocyclones that occurs when the boundary layer convection is more vigorous. Nowotarski et al. (2012) found that horizontal convective rolls (HCRs), which are present in a thermally driven convective boundary layer with vertical shear (e.g., Weckwerth et al. 1997), can influence the morphology of simulated supercells; horizontal vorticity associated with them, when tilted vertically, can produce vertical vorticity. This vorticity can then be enhanced underneath updrafts (e.g., Wilson et al. 1992).

b. Tornado dynamics and structure

The depth of the *friction layer* (the viscous sublayer next to the ground) in an axisymmetric, steady-state tornado, whose radial profile of azimuthal wind is that of a potential vortex, has been shown theoretically to be $\sim(\nu/\Gamma)^{1/2}r$, where ν is the kinematic coefficient of turbulent viscosity, Γ is the angular momentum in the

outer region, and r is the distance from the axis of rotation (radius) (Burggraf et al. 1971). The depth of the friction layer is, for example, only ~ 10 m for $\nu \sim 10^3 \text{ m}^2 \text{ s}^{-1}$ (Bluestein 2013) at a core radius of 100 m, and for angular momentum in the outer layer when at the core radius the azimuthal wind speed is 75 m s^{-1} . It may be inferred from the large-eddy simulation experiments of Lewellen et al. (2000) that the depth of the friction layer is ~ 0.15 times the core radius (e.g., Fig. 1 in Lewellen et al. 2000), which is in accord with theory.

Inside the core radius, the “corner-flow region,” where there is solid-body rotation, there is no friction layer (Wilson and Rotunno 1986), but to the best knowledge of the authors, there is no observational evidence from tornadoes in nature to test this inference.

For a tornado over a disk of radius a (where the boundary layer begins and then spreads inward) with potential flow, the depth of the *inertial layer* (where the flow is not in cyclostrophic balance, between the friction layer below and the outer region, which is in cyclostrophic balance, above) is $\sim(\nu/\Gamma)^{1/2}a$ (Burggraf et al. 1971); for $a \sim 1$ km, the radius of the parent vortex, the inertial layer is ~ 100 m thick. In Lewellen et al. (2000) it is seen that in large-eddy simulations the depth of the inertial layer is ~ 0.5 times the core radius (e.g., see Fig. 1), which is therefore also in accord, at least roughly, with theory (see also Wilson and Rotunno 1986, their Fig. 17).

c. Deficiencies of radar measurements in tornadoes and supercells

To resolve well features of a specified spatial scale (i.e., so that any increase in the number of equally spaced samples does not significantly alter the shape of the feature), measurements are needed at a rate of at least 10 per scale length (Gal-Chen and Wyngaard 1982), which is well above the Nyquist rate; in practice, however, for many purposes as few as 6 may suffice. Thus, mapping out vertical variations in the wind in the tornado boundary layer requires a radar beam that is ~ 10 – 15 m deep in the inertial layer and ~ 1 – 1.5 m deep in the surface boundary layer and probably also in the corner region (Fig. 1).

Such spatial resolution is often difficult, if not impossible, to attain with radars because there can be significant ground-clutter contamination. Furthermore, owing to the curvature of the earth, under typical atmospheric refractivity conditions, the friction layer is not probed when the radar antenna is 2 m above the ground and the elevation angle is 0° , beyond ~ 10 -km range from the tornado; even the inertial layer will not be probed at that range when the elevation angle is only $\sim 0.5^\circ$.

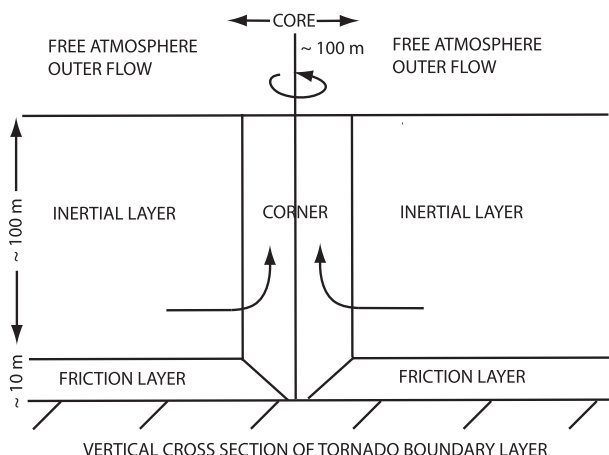


FIG. 1. Idealized vertical cross section of a tornado boundary layer. The core of the tornado is ~ 100 m in radius. The lowest layer, the *friction layer*, where the main force is surface drag, is ~ 10 m deep and characterized mostly by flow in the radial direction. Above the friction layer, the *inertial layer*, where a radially inward-directed pressure gradient force overwhelms an outward-directed centrifugal force, is ~ 100 m deep and also characterized mostly by flow in the radial direction. Above the boundary layer there is the free atmosphere, or the *outer-flow region*, where the flow is mainly swirling. The depth of the friction layer decreases toward the center of the tornado; above the ground, within the core radius, but no higher than the top of the inertial layer, is the *corner* region, which is characterized by both radial and swirling flow. The swirling flow above the boundary layer, within the core, is depicted by a curling streamline; radial inflow and turning upward of a streamline in the vertical plane are shown as streamlines in the inertial layer.

In addition, although radars can detect air motion in both clear air and in precipitation, the dynamic range of the radar may be less than that required to resolve both clear-air return and backscattering from nearby intense precipitation. Also, in order to detect clear-air motions, the pulse duration may have to be increased at the expense of range resolution.

d. The case for the use of Doppler lidars along with radars

Doppler radars, particularly mobile radars deployed at close range (< 30 km), have been used to probe supercells and tornadoes and produce analyses of the wind field (e.g., Bluestein et al. 2007a,b, 2010; Wurman et al. 2012, 2013). Owing to the spreading of the radar beam with range, typical X-band radar antennas, which have a half-power beamwidth $\sim 1^\circ$ (e.g., Wurman et al. 2012; Bluestein et al. 2007b; Burgess et al. 2011; Pazmany et al. 2013), are constrained to have an azimuthal resolution on the order of 100 m at ranges ~ 5 –10 km. Even a W-band Doppler, which had a half-power beamwidth of only 0.18° (e.g., Bluestein et al. 2007b), is constrained to have an azimuthal resolution of 15–30 m at a range of 5–10 km. It therefore cannot *map* out the wind field in

the surface layer except on those rare occasions when the tornado is dangerously close, that is, within ~ 500 m. Range resolutions of ~ 30 –150 m are typical at X band; higher-powered radars can achieve the highest resolution (Wurman et al. 2012), while others require nearby features having intense reflectivity. To detect clear-air motions, the pulse length can be increased to enhance the radar's sensitivity, but by doing so, the radial resolution is decreased.

To increase the azimuthal resolution, one may use a pulsed Doppler lidar that sends out a collimated beam of light ~ 10 cm across and does not spread with distance from the lidar within range of the lidar's far field.¹ Typical solid-state lidars have range resolutions as short as ~ 20 m (Pearson et al. 2009), which is about as short as that achieved by some mobile radars (~ 15 –30 m). In addition, a typical lidar beam does not penetrate cloud and precipitation very well or at all; it does require a sufficiently high concentration of aerosol in "clear air," which limits its effectiveness at higher altitudes, but is quite suitable for probing the atmospheric boundary layer. Furthermore, there is no sidelobe contamination from a collimated beam.

A (continuous wave) Doppler lidar was first used by Schwiesow et al. (1981) to obtain Doppler wind spectra in waterspouts from an aircraft flying over the Florida Keys. McCaul et al. (1987) used an airborne pulsed system to map the wind field in gust fronts and non-precipitating convective clouds. DeWekker et al. (2012) also used an airborne system to map the wind field for topographically forced flows in the boundary layer over coastal terrain in California. Ground-based, pulsed Doppler lidars have been used many times to map the finescale structure of clear-air phenomena close to the earth's surface, including surface boundaries and orographically forced flows (Table 1).

The two main purposes of this paper are 1) to describe qualitatively ground-based wind observations in the boundary layer in and near supercells (mostly in the inflow region and just behind the rear-flank gust front), some tornadic, from a very high-spatial resolution, mobile, pulsed Doppler lidar and collocated, mobile, phased-array, X-band Doppler radar data (Bluestein et al. 2010); and 2) to make a case for the use of the lidar for probing the boundary layer of tornadoes. The data were collected during the second year of the Second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) (Wurman et al. 2012). The

¹ The far-field range is given by the aperture squared divided by the wavelength; for the lidar to be described, the far field is at most ~ 10 km.

TABLE 1. Selected studies of small-scale, clear-air phenomena* using ground-based, pulsed Doppler lidars.

Phenomena and location	Citation
Gust fronts, eastern Colorado	Rothermel et al. (1985)
Downslope windstorm, Front Range of the Rockies	Neiman et al. (1988)
Retreating dryline, West Texas	Parsons et al. (1991)
Sea breeze, California	Banta et al. (1993)
Orographically forced mesoscale vortex, Front Range of the Rockies	Levinson and Banta (1995)
Drainage flows, Front Range of the Rockies	Levinson and Banta (1995)
Gap flow, Alps	Weissmann et al. (2004)
Strong-wind boundary layer near the nocturnal low-level jet, Kansas	Banta et al. (2006)
Rotors, etc., in downslope windstorms, lee of the Sierra Nevada	Hill et al. (2010), Kühnlein et al. (2013)

* This list is nonexhaustive and is meant only to demonstrate the diversity of phenomena studied with data from ground-based, pulsed Doppler lidars.

data collection represents a new application of the combined use of a lidar and a novel, mobile phased-array radar, applied to studies of severe convective storms. Section 2 contains a brief description of the lidar and radar systems and the methodology used to collect the data. Descriptions of the combined datasets through brief case studies are detailed in section 3, and a summary and suggestions for future field programs are found in section 4.

2. Instrumentation and methodology of deployment and data collection

a. Description of the lidar system

The pulsed Doppler lidar system, the Truck-Mounted Wind Observing Lidar Facility (TWOLF), is a 2- μm wavelength, coherent system (Fig. 2; Table 2) once commercially available (the latest version operates at 1.6 μm ; <http://www.lockheedmartin.com/us/products/windtracer.html>) from Lockheed Martin Coherent Technologies (LMCT) for ground-based applications and was first installed on a U.S. Navy Twin Otter aircraft and used in 2002 (De Wekker et al. 2012). Having been used to map the wind field off and over the coast of California, it was mounted on the MWR-05XP (Mobile² Weather Radar–2005 X-band, phased array) truck platform (Bluestein

et al. 2010) and tested by the first author during the summer of 2009 near Boulder, Colorado, during a gust front passage, for use during VORTEX2. TWOLF's use during VORTEX2 was essentially the first field experiment in which it was used to probe meteorological features near severe convective storms near the ground.

Technical details about the lidar system are found in DeWekker et al. (2012). Other details about signal processing techniques and error analyses relevant to Table 1 are found in Frehlich (2001, 2004). A 10-cm-wide collimated beam is directed via a hemispherical scanner mounted on the top of the truck's cab (Fig. 2a), adjacent to the phased-array antenna of MWR-05XP. The scanner can be programmed to rotate slowly about each of two axes (in azimuth and elevation). Several deployments are depicted for illustrative purposes in Fig. 2; the truck must be oriented so that the radar antenna from the MWR-05XP does not block the lidar beam as TWOLF scans a target area. The range of the lidar is typically no greater than 10–15 km within the convective boundary layer. During VORTEX2, priority was given to the collection of MWR-05XP data, so there were some instances when the radar antenna blocked the lidar beam and when the range to the target storm was beyond 10 km. In these instances, data were collected mainly in the approximate direction from which the low-level wind was blowing.

Doppler velocity, spectrum width, and signal-to-noise ratio (SNR) estimates are available at each range gate. The SNR may be used as a substitute for reflectivity. However, the backscatter cross section is related to not only the concentration of aerosol but also to its composition. When there is vigorous mixing of aerosol of the same composition, the concentration should be uniform; in regions where mixing is inhibited or there are larger aerosols, there could be a large variation in backscatter from the aerosols. When there are cloud droplets or precipitation, the signal could be (and often was) completely attenuated. One must be careful *not* to interpret the SNR measured by lidars in exactly the same way the radar reflectivity factor is interpreted for radar data. The SNR data were corrected for range using very crude assumptions on extinction and are to be interpreted only in a very qualitative sense. In some cases it might be possible to discriminate between targets moving at different velocities in the same volume, from frequency spectra computed from either Doppler radar or Doppler lidar data. The latter may be the case in the boundary layer of a tornado where more massive particles are being ejected from the closed circulation by centrifugal forces (Dowell et al. 2005), while the less massive particles are better tracers of the actual azimuthal wind component.

² In Bluestein et al. (2010), the moniker “Meteorological” is incorrectly used; the correct moniker is “Mobile.”

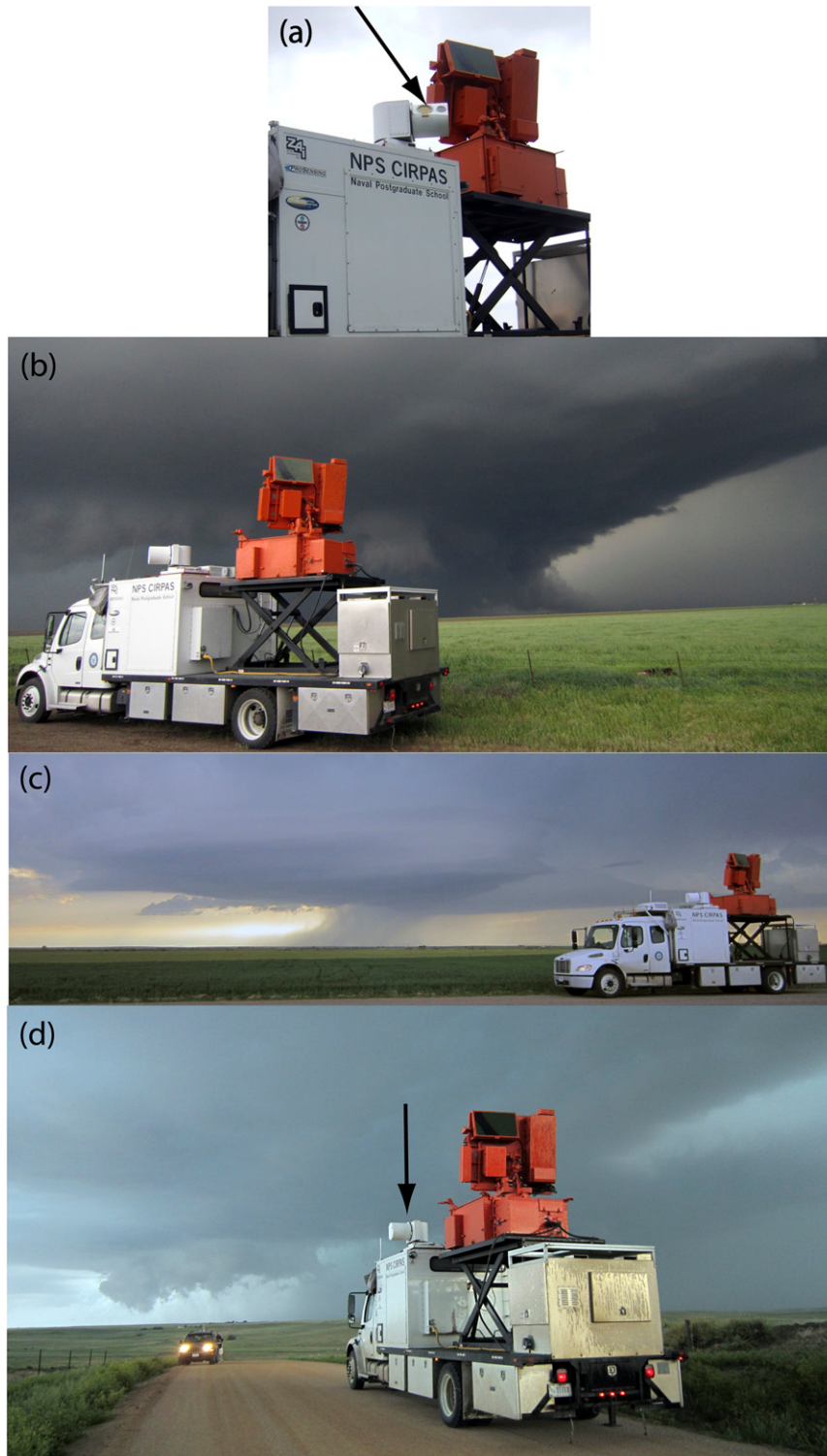


FIG. 2. TWOLF and MWR-05XP collecting data in the field as seen from several viewing angles. (a) Close-up of the front side of the lidar telescope (arrow) mounted on the cab of the truck and the back side of the radar antenna (to the right) during testing on 29 Jul 2009 near Boulder as a gust front passed. (b) Probing a supercell in the northern Texas Panhandle at ~ 0018 UTC 19 May 2010. (c) As in (b), but in eastern Colorado at ~ 2355 UTC 10 Jun 2010. (d) As in (b), but south of Limon at ~ 2356 UTC 11 Jun 2010. Arrow points to the back of the lidar telescope in (a) and (d). (Photographs courtesy of H. Bluestein.)

TABLE 2. Characteristics of TWOLF.

Wavelength	2 μm (eye safe)
Energy/pulse	2 mJ
Pulse length (temporal, spatial)	320 ns, 48 m
Pulse repetition frequency	100 Hz (500-Hz maximum capability)
Range gate length	96 m
Range gate resolution	50 m
Line-of-sight measurement accuracy*	$\sim 0.2 \text{ m s}^{-1}$
Wind-component accuracy*	$< 0.5 \text{ m s}^{-1}$

* Based on use in an aircraft; actual accuracies depend on specific atmospheric conditions and other factors.

While Doppler radar velocity data can usually be dealiased, TWOLF Doppler velocity data cannot be dealiased. The lidar, which is ~ 15 years old, was originally designed for use at airports to produce vertical profiles of the horizontal wind component through velocity–azimuth displays (VADs) and to detect vortices generated by aircraft; Doppler velocities were not expected to be very high. Doppler spectra are computed using only one digitizer and hence only the real component of a fast Fourier transform is calculated; consequently, for example, a velocity slightly in excess of the maximum outbound does not fold back onto the interval of inbound velocities but instead folds back onto the outbound velocities, leading to ambiguities in velocity that cannot be resolved. Hence, an antialiasing filter is applied, so Doppler velocities beyond the Nyquist interval are simply not detected.

The TWOLF lidar can detect Doppler velocities with deviations of $\pm 25 \text{ m s}^{-1}$ from a reference velocity (e.g., the motion of the platform on which it is mounted), when there is an analog front end (AFE) to account continuously for the speed of the platform. However, when scanning across a tornado from a stationary, ground-based platform, the center frequency shift must be accomplished by the AFE automatically relatively quickly to account for the much larger dynamic ranges in Doppler velocity in tornadoes ($\sim \pm 50 \text{ m s}^{-1}$ or greater). In 2010, it was not possible to change the center frequency automatically, so the lidar was most suitable for probing boundary layer flow and weaker vortices such as mesocyclones for which the Doppler velocities are typically within $\pm 25 \text{ m s}^{-1}$.

b. Description of the radar system

The MWR-05XP is a hybrid, phased array and mechanically scanning, X-band, mobile Doppler radar used to probe supercells and tornadoes (Bluestein et al. 2010; French et al. 2013). For the purpose of illustration, it is noted that it can scan volumes by collecting data at

14 elevation angles (1° – 20°) simultaneously across a 90° sector in ~ 7 s. The half-power beamwidth is 1.8° in azimuth and 2° in elevation; the range resolution is 150 m, while measurements are oversampled every 75 m. The spatial resolution is approximately only half that of most mobile, X-band radars (e.g., Wurman et al. 2012), but it is adequate for sampling storm-scale features at short range (out to ~ 30 km). The radar scans electronically in elevation and mechanically in azimuth at speeds up to 180° s^{-1} ; it also back scans electronically over a limited azimuth to keep the beam quasi stationary for short periods of time. Frequency hopping is also employed to increase the number of independent samples obtained. Ground clutter cannot be removed from the radar data without significantly sacrificing the scanning speed.

c. Methodology of deployment and data collection

Deployments were made during VORTEX2 with the objective of collecting data near the main updraft region of supercells and in surrounding areas. The MWR-05XP was to be used to collect storm-scale data in regions of precipitation, or in regions of high insect or dust concentration in clear air, and TWOLF was to be used to make simultaneous boundary layer measurements in clear air. Accordingly, efforts were made to deploy MWR-05XP/TWOLF ~ 10 km to the right of the motion of the updraft/wall cloud region of supercells.

The truck was deployed over roads as flat as possible, but levelers were not available. Stabilizers, however, were used only to prevent shifting of the position of the truck; the inclinometer system that was supposed to detect roll and pitch angles was not functioning. It was estimated that the tilt of the road on which the truck was deployed was rarely more than 3° , so that for ranges of 10 km or less the estimated beam height AGL could have been as much as ~ 500 m in error. In any event, wind analyses from both TWOLF and MWR-05XP at corresponding elevation angles should correspond to the same altitudes because the two instruments are mounted on the same truck.

Volumetric update times for the MWR-05XP varied from ~ 6 to ~ 15 s. The desired scanning rate for the TWOLF was $\sim 3^\circ \text{ s}^{-1}$. Limited-azimuth sector scans for TWOLF took ~ 30 s and range–height indicators (RHIs; i.e., vertical cross sections at a constant azimuth) took ~ 15 – 30 s (corresponding to 45° and 90° sectors, respectively). Owing to the relatively slow scanning rate of TWOLF, the main modes of data collection were limited-azimuth sector scans at one elevation angle and RHIs. Some volume scans were collected, but owing to the relatively long time between scans the corresponding temporal continuity in the vertical is not sufficient to resolve vertical structures well if there was significant

evolution of the wind field in between scans. The truck was positioned so that TWOLF could collect data in the clear air between the truck and the precipitation region to the rear of the rear-flank gust front and the forward-flank core, while the MWR-05XP could collect data in the aforementioned precipitation regions and possibly clear air in the same areas covered by TWOLF. The RHIs were collected in the approximate direction of the surface wind, either in the direction from which it was blowing or in the direction toward which it was blowing.

3. Case studies

Selected cases of combined TWOLF and MWR-05XP data on 10, 18, 25, and 26 May, and 10 June 2010 are discussed. The purpose of showing these cases is to demonstrate that lidar data can add value to radar data. In particular, the lidar data in these cases are used to identify HCRs (and the spacing of the rolls) or the lack thereof and features that may or may not be detected also by the radar.

a. 10 May 2010: Tornadoic supercell in eastern Oklahoma

Dozens of tornadoes were reported in central and eastern Oklahoma and in southern and western Kansas on 10 May 2010. More details about this case may be found in Burgess et al. (2011). Data were collected in eastern Oklahoma, just west of Wetumka, Oklahoma, as the hook echo from a supercell to the north passed just to the north and northeast of the deployment location (Figs. 3b,c). A tornado was reported near Clearview, Oklahoma, to the northeast, just after data collection had ended. From our vantage point, we could see a broad, lowered cloud base to the northeast, but trees blocked our view of the ground; a video frame grab from a VORTEX2 participant (Fig. 3a) showed only a narrow condensation funnel, though a wider funnel may have existed at another time. According to a damage survey by the National Weather Service Office in Norman, Oklahoma, the tornado began just to our northwest, 6.5 mi (~ 10.4 km) south of Okemah, Oklahoma, near I-40, or about 13–15 km away, and ended to our northeast, 2.75 mi (4.4 km) north-northwest of Pharaoh, Oklahoma, just north of I-40; it lasted from 2345 to 0010 UTC, was rated at EF-1 intensity, had estimated peak winds of 105 mph (~ 47 m s $^{-1}$), and a maximum path width of 1000 yards (~ 1 km).

Although trees blocked low-altitude scans to the northeast of the MWR-05XP (Figs. 3b,c; data within 10 km and clockwise from the $\sim 20^\circ$ radial appear to be blocked), a well-defined hook echo and mesocyclone (2.5 km wide across the Doppler velocity extrema) were

evident; maximum wind speeds of ~ 35 m s $^{-1}$ were seen in the approaching direction (Fig. 3c). Data were collected while damage was being inflicted.

TWOLF data were collected in the eastern and southeastern sectors (Fig. 3d) at an elevation angle high enough that the lidar beam went above nearby trees; the radar antenna blocked the view to the northeast, where the tornado was located, and precluded data collection in it, although it was beyond the range of the lidar anyway. The 0 m s $^{-1}$ isodop was oriented approximately in the east–west direction, which is consistent with a southerly wind at the surface (Fig. 3e). While there was some finescale structure (variations of several m s $^{-1}$) in the Doppler velocity field, there was no clear evidence of any banded structures and hence not of any HCRs. For this case, then, no evidence is found that HCRs played any role in tornadogenesis.

b. 18 May 2010: Tornadoic supercell in the northern Texas Panhandle

MWR-05XP and TWOLF were deployed well to the east of a supercell in the northern Texas Panhandle on 18 May 2010 since it was anticipated that it would move much closer, toward the region just to the northwest of the instruments. More details about this case may be found in Skinner et al. (2013, manuscript submitted to *Mon. Wea. Rev.*). At a far range of 35 km or more, the spatial resolution of the MWR-05XP precluded resolving the finescale structure of the Doppler wind field in the storm, but a hook echo could be discerned (Fig. 4a), along with strong storm-relative low-level inflow (Fig. 4b; red-shaded area), and evidence of a rear-flank gust front (Fig. 4a; concave radar echo connected to the southeastern portion of the hook and Fig. 4b; curved convergence line indicated by 0 m s $^{-1}$ isodop separating inflow coded yellow from outflow coded green). There was insufficient backscattering from targets within ~ 20 km of MWR-05XP to estimate Doppler velocities. However, TWOLF was sensitive enough to indicate flow away from the lidar, toward the storm (Fig. 4c). Since the 0 m s $^{-1}$ isodop was oriented in the northeast–southwest direction, a southeasterly wind direction is suggested, which is consistent with the surface wind observations (Fig. 4d). No well-defined finescale structure was evident in the Doppler lidar wind field; thus, no HCRs were discernible.

A cross section of data in a vertical plane (RHI) between the lidar and the storm (Fig. 5a) indicates a component of flow toward the storm in the lowest 1.5 km, with increasing speed with range below 1 km AGL; either the low-level inflow into the storm increased near the storm or the surface wind backed from a more southerly direction to a more easterly direction. The

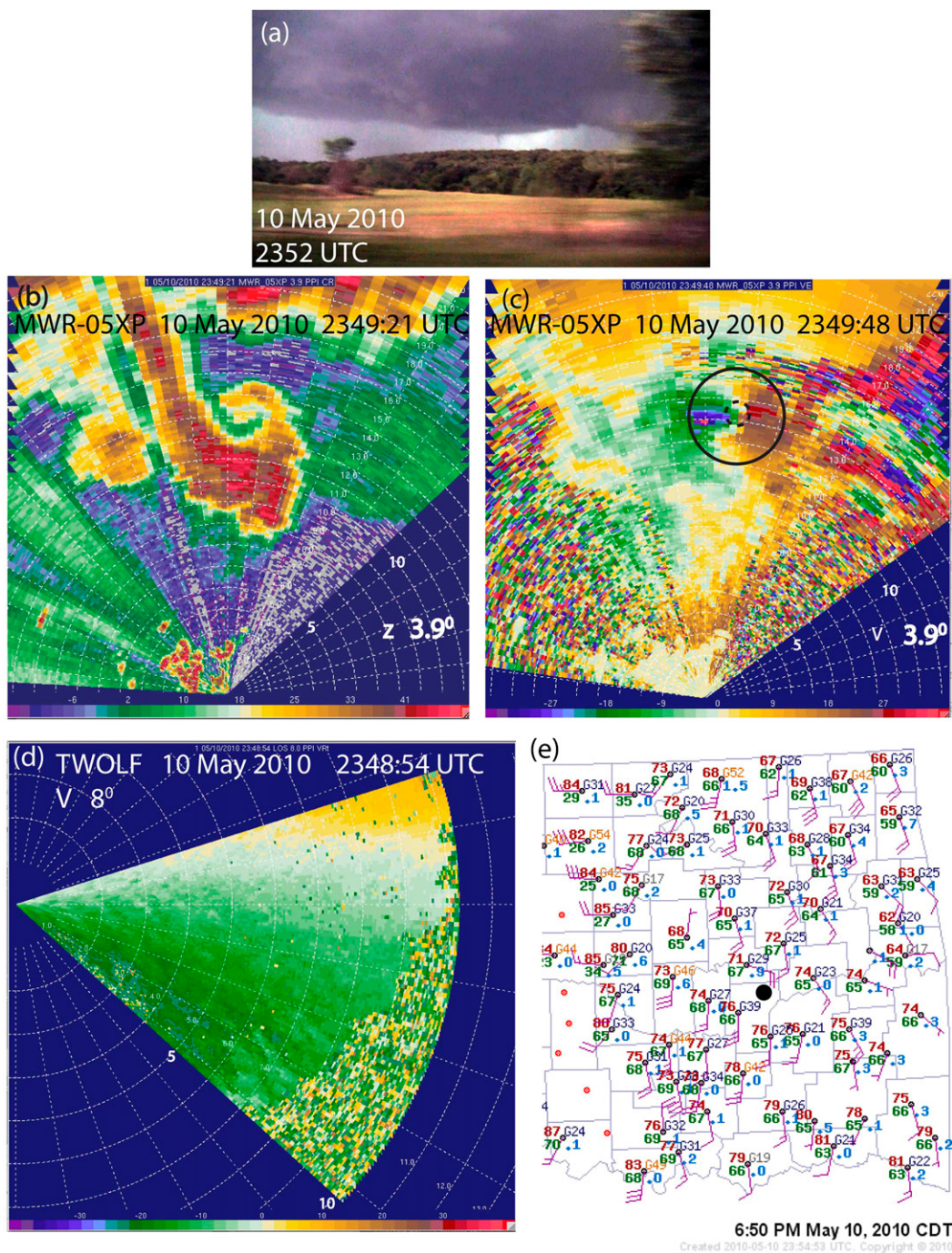


FIG. 3. (a) National Severe Storms Laboratory (NSSL) photograph of the Clearview tornado, as seen to the northwest, from a mobile Mesonet at ~2352 UTC 10 May 2010, ~3.5 km south-southwest of Weleetka, Oklahoma, courtesy of Kiel Ortega. Storm-scale view of (b) Z_r (dBZ_r) and (c) Doppler velocity (V , m s^{-1}) from MWR-05XP, at 3.9° elevation angle (here and elsewhere, the elevation angle is only approximate because the truck was not leveled), at 2349:21 UTC for radar reflectivity and 2349:48 UTC for Doppler velocity. Range rings shown every 1 km; data collected from a location 3.6 km west of Wetumka. The solid black circle encloses the mesocyclone signature; the dashed black circle may mark the tornado. Range rings shown every 1 km. (d) Doppler velocity (m s^{-1}) from TWOLF, at 8° elevation angle, at 2348:54 UTC 10 May 2010. Range rings shown every 1 km. (e) Surface observations plotted from the Oklahoma Mesonet at 2350 UTC 10 May 2010. The black dot marks the approximate location of TWOLF/MWR-05XP. Temperature (red) and dewpoint (green) plotted (°F); whole (half) wind barbs indicate 5 (2.5) m s^{-1} . (In this and subsequent figures, north is directed to the top of the page for all radar and lidar imagery. Also, the color scales given at the bottom of each panel are shown for the variables depicted, e.g., for radar reflectivity factor, Doppler velocity, or SNR; the numbers plotted are for the color scales and do not denote distance.)

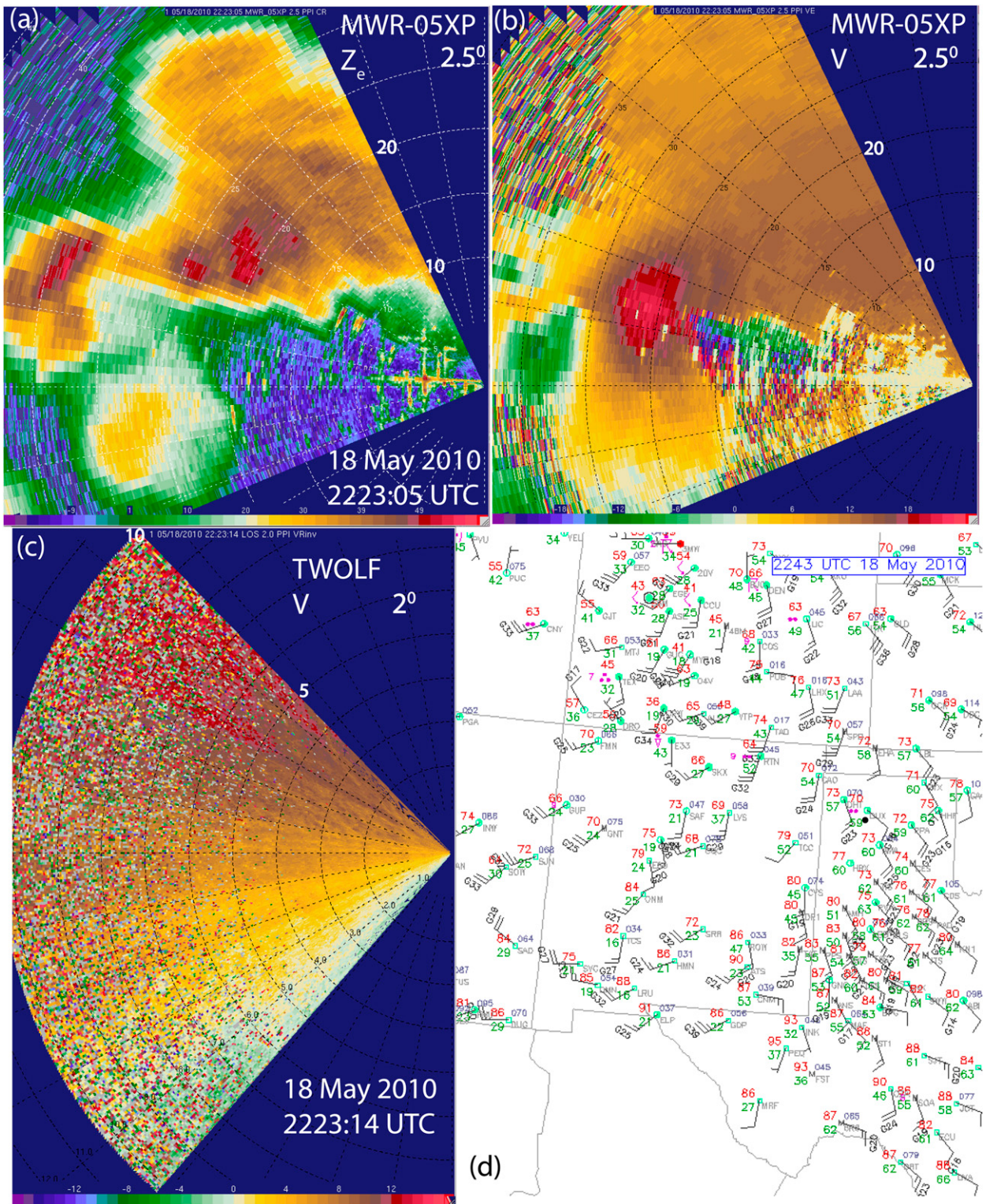


FIG. 4. Storm-scale view of (a) Z_e (dBZ_e) and (b) V (m s^{-1}) from MWR-05XP, at 2.5° elevation angle, at 2223:05 UTC 18 May 2010, ~10 km southwest of Dumas, Texas. Range rings shown every 5 km. (c) Doppler velocity V (m s^{-1}) from TWOLF, at 2° elevation angle, at 2223:14 UTC 18 May 2010. Range rings shown every 1 km. (d) Surface map, as in Fig. 3d, but from conventional surface data, at 2243 UTC 18 May 2010. The black dot marks the approximate location of TWOLF/MWR-05XP.

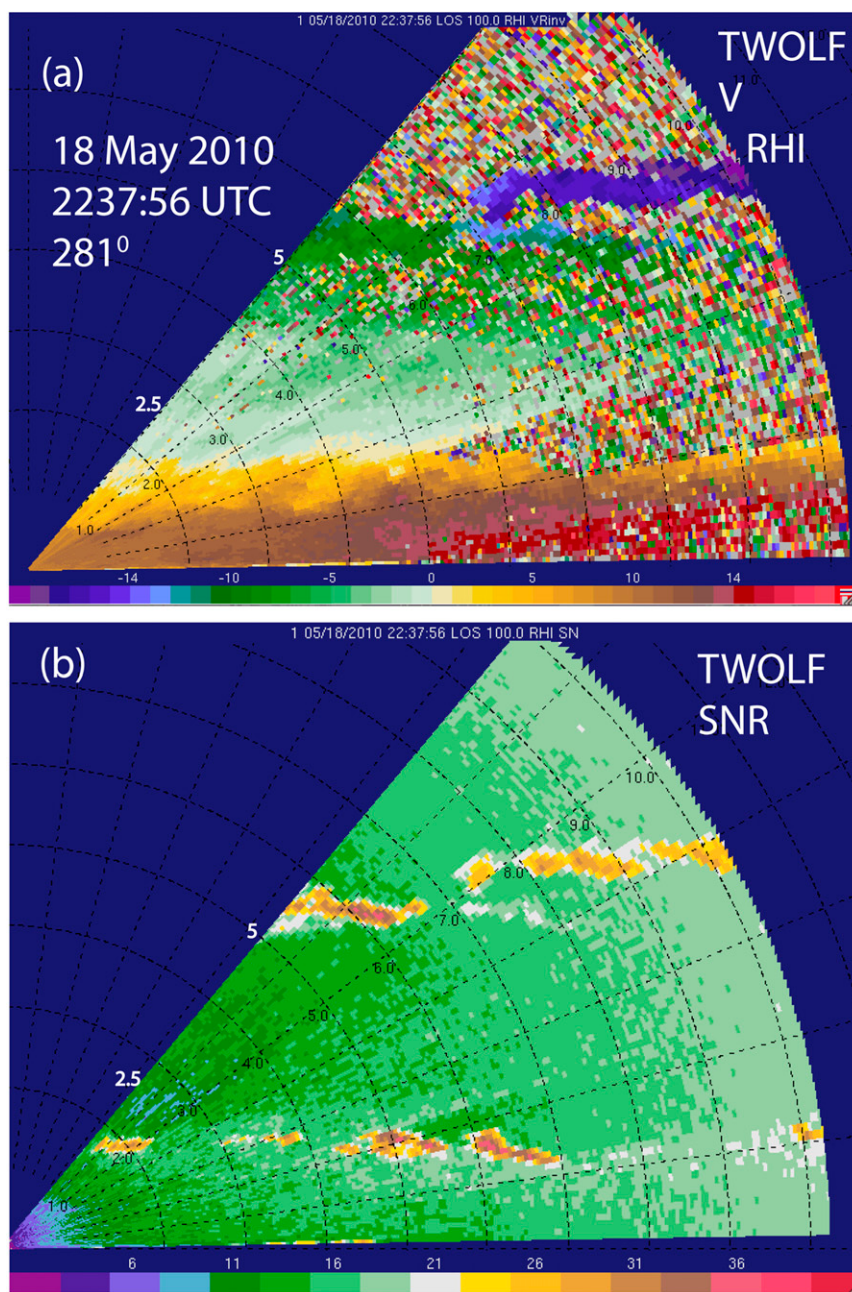


FIG. 5. Vertical cross sections (RHIs) of TWOLF (a) Doppler velocity (V , m s^{-1}) and (b) SNR (dB), at 2237:56 UTC 18 May 2010, looking in the west-northwest direction (281°) from the same location as that for Fig. 5. Range rings shown every 1 km.

flow above has a component toward the lidar. There is vertical shear in the lowest 4 km in approximately the east–west direction of $\sim 25 \text{ m s}^{-1}$, which is considered relatively strong (e.g., Grams et al. 2012). There is some spatial variation in the 0 m s^{-1} isodop, but no well-pronounced patterns can be identified. Two layers of higher SNR are seen (Fig. 5b): one is at $\sim 1.5 \text{ km AGL}$ and the other is $\sim 4 \text{ km AGL}$. The top layer, which marks

the top edge of data collection, probably represents the bottom surface of the anvil from the storm, above which attenuation from cloud material and/or precipitation blocked further penetration of the lidar beam. The bottom layer probably marks the top of the moist boundary layer and may be caused by an increase in aerosol concentration underneath the stable layer at the top of the boundary layer (not shown). A brief tornado

was reported with the storm at 2236 UTC, just a minute earlier than the data displayed in Fig. 5.

Later, at 0114:52 UTC 19 May 2010, MWR-05XP and TWOLF were deployed just to the south of the storm as it passed by Stinnett, Texas. A hook echo (Fig. 6a) and several embedded vortex signatures (Fig. 6b) were resolved by MWR-05XP at or within 12-km range; two were cyclonic and one anticyclonic. Ground clutter and otherwise noisy, clear-air data were seen by MWR-05XP at ranges closer than ~ 6 km. TWOLF, however, was able to resolve boundary layer features within ~ 8 -km range. Prominent linear bands of Doppler velocity oscillations oriented in the north-northwest to south-southeast direction, with a wavelength of ~ 500 m, were resolved (Fig. 7a). It is likely that these bands are evidence of HCRs. The far edge of the area within which data above the noise level were collected coincides with a thin band of enhanced SNR (Fig. 7b). From Fig. 6a, it is seen that this band approximately coincides with the inner edge of a region of radar reflectivity factor of ~ 5 – 10 dBZ_e. While measurements with MWR-05XP appear contaminated within ~ 5 – 6 -km range, it is therefore plausible that the thin band seen in Fig. 7b marks the leading edge of some very light precipitation or drizzle.

c. 25 May 2010: Tornadoic supercell in far western Kansas

Data were collected by MWR-05XP (Figs. 8a,b) while a tornado was in progress and by TWOLF (Fig. 8c) in between successive tornadoes (Figs. 8d,e); the tornadoes were produced cyclically, by a supercell that moved across the Colorado–Kansas border into far western Kansas. More information on this case can be found in Tanamachi et al. (2013a) and French et al. (2014). At the time data were collected, two adjacent supercells were evident in MWR-05XP radar reflectivity data (Fig. 8a). Cyclonic vortex signatures (Fig. 8b) were located near the two hook echoes seen in Fig. 8a. The signature to the northeast was associated with the previous tornado; it is likely that the new vortex signature evident near the hook echo in the southwesternmost supercell evolved into the tornado seen in Fig. 8e, but this assertion cannot be proven because data collection ceased at 2336 UTC and MWR-05XP and TWOLF moved on to redeploy to a location to the northeast. MWR-05XP data appear to be contaminated with ground clutter within ~ 3 -km range, especially to the northeast, as evidenced by a splotchy equivalent radar reflectivity field Z_e and a noisy Doppler velocity field (Doppler velocities alternate from yellow/white to green, that is, from approaching to receding velocities over relatively short distances).

TWOLF Doppler velocity data, however, exhibit no contamination from ground targets (Fig. 8c). Flow is mainly toward the lidar in the northeastern sector and away from the lidar in much of the northwestern sector. Although there is no well-defined 0 m s^{-1} isodop oriented in the north–south direction, the Doppler velocities do trend from approaching to receding with distance to the west, which is suggestive of easterly flow. This flow pattern is consistent with the Doppler-velocity pattern seen in the MWR-05XP data in the southwestern supercell (Fig. 8b), particularly just to the southeast of the vortex signature. There is some hint of banding of Doppler velocities in Fig. 8c, especially where there are a few alternating bands of approaching or stagnant (green or white) and receding (yellow) Doppler velocities oriented approximately in the north–south direction. It is possible that these bands are evidence of HCRs. In this case, the spacing between bands is ~ 500 m, as noted before in the 18 May 2010 case.

d. 26 May 2010: Supercell in northeastern Colorado with strong low-level vortices

A supercell that had produced tornadoes near Denver, Colorado, subsequently produced many low-level vortices, none of which was associated with any tornado. Further details on this storm may be found in Tanamachi et al. (2013a). The supercell at the time of data collection south of Wiggins, Colorado, had, evident in MWR-05XP data, a hook echo (Fig. 9a) and a strongly divergent, cyclonic vortex signature (Fig. 9b) at ~ 11 -km range, beyond the 6–7-km range of TWOLF. The visual appearance of the supercell 14 min earlier is depicted in Fig. 9e; a precipitation-free updraft base and precipitation falling to the northwest are seen. While the Doppler radar reflectivity factor and Doppler velocity fields from MWR-05XP appeared to suffer from significant ground-clutter contamination within ~ 5 -km range, the TWOLF Doppler velocity field (Fig. 9c) did not. Streaks in Doppler velocity minima can be seen, but no well-defined bands are evident; strong evidence for HCRs is therefore not found. The strongest receding Doppler velocities ~ 10 – 15 m s^{-1} to the northwest are consistent with the southeasterly surface winds plotted from the standard network of observing stations (Fig. 9d); however, the lidar winds, which are valid at the 3° elevation angle (~ 130 m AGL at 2.5-km range), are less than the 10 – 11 m s^{-1} southeasterly winds indicated by the network.

e. 10 June 2010: Nontornadoic and tornadoic supercell in eastern Colorado

Data were collected at several deployment locations for relatively long periods of time.

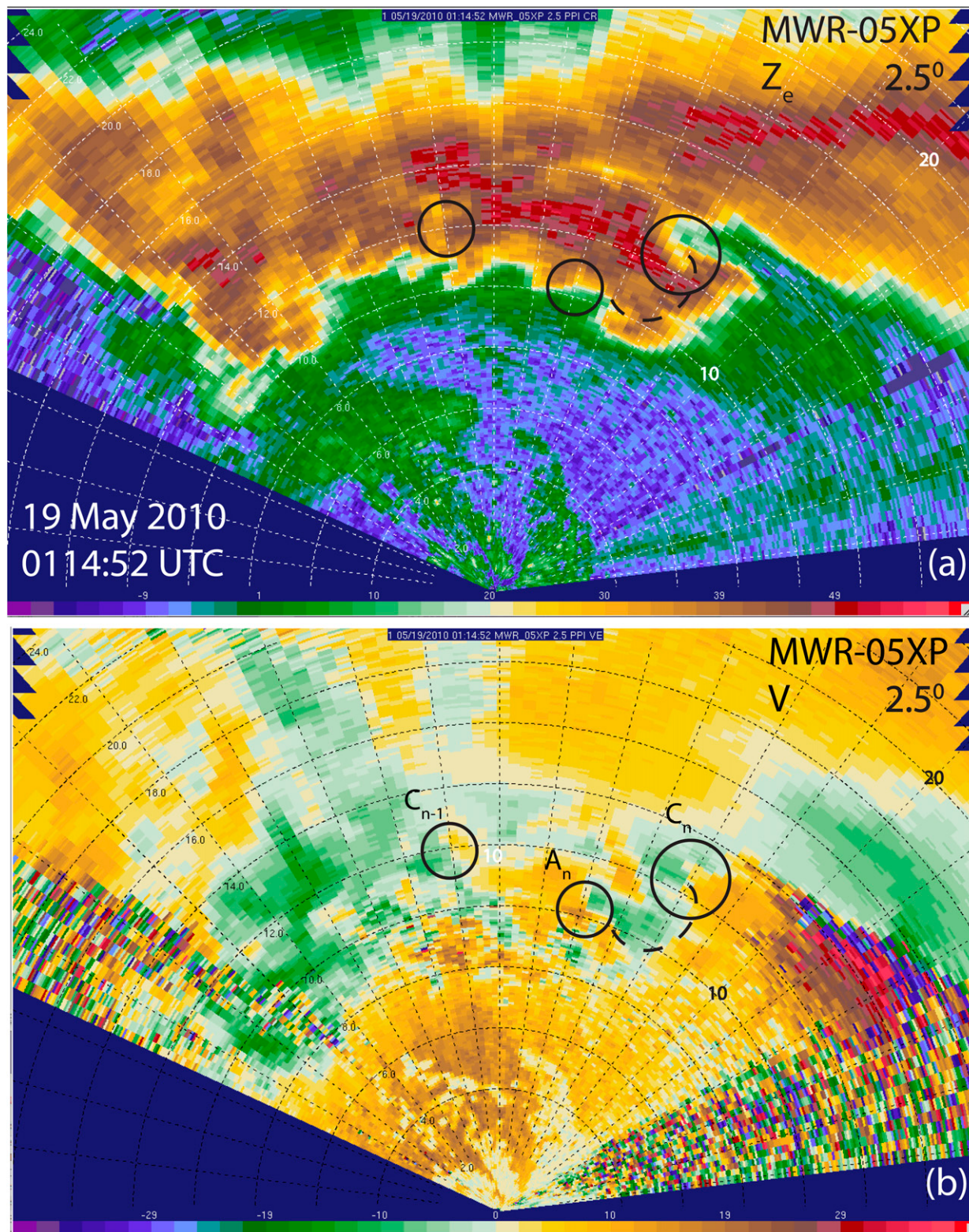


FIG. 6. Storm-scale view of (a) Z_e (dBZ_e) and (b) V (m s⁻¹), from MWR-05XP, at 2.5° elevation angle, at 0114:52 UTC 19 May 2010, 3.8 km southeast of Stinnett, Texas. Circles C_i and A_i highlight cyclonic and anticyclonic vortex signatures, respectively, at times $i = n - 1$ and n . Range rings shown every 2 km.

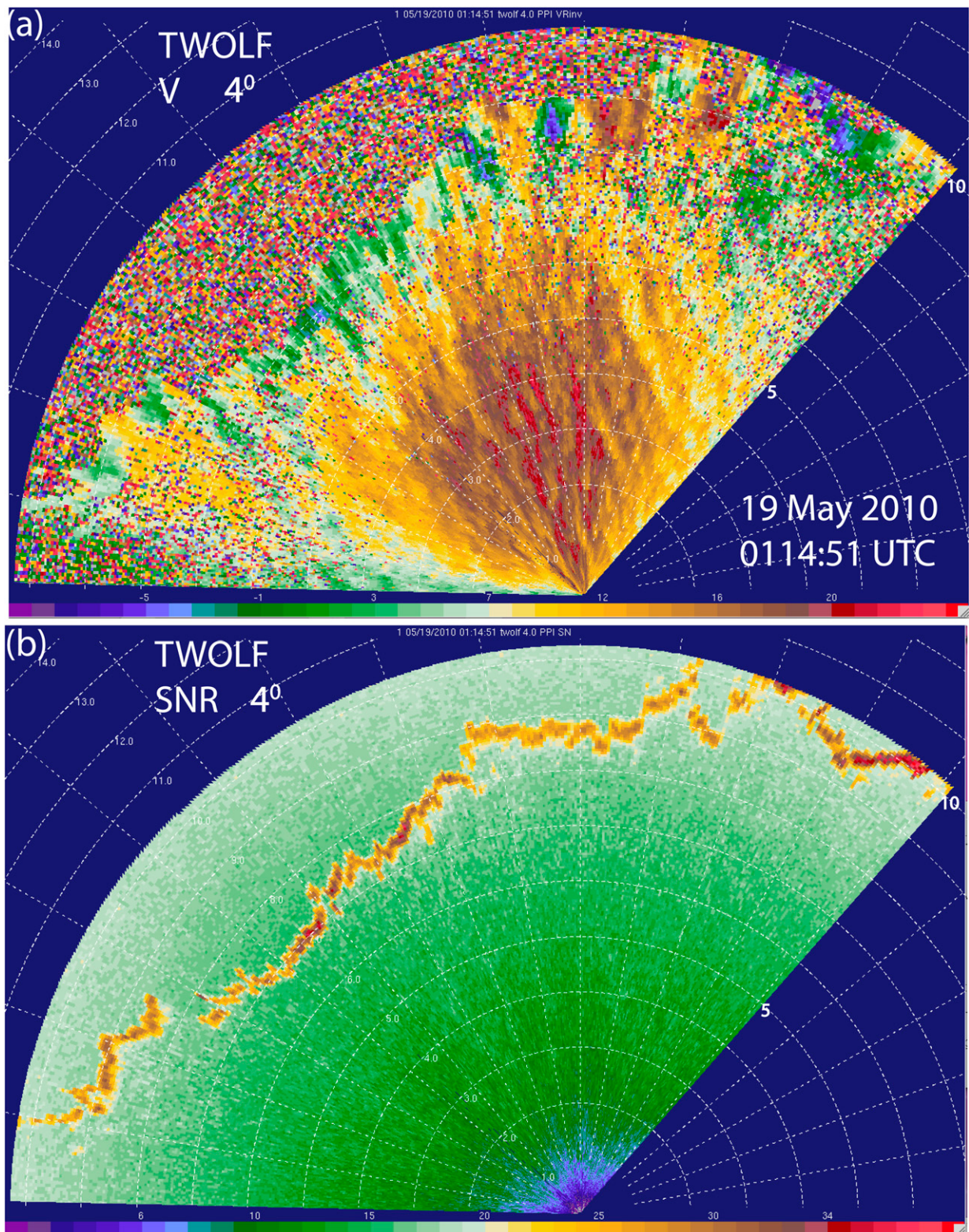


FIG. 7. (a) Doppler velocity V (m s^{-1}) and (b) SNR (dB) from TWOLF, at 4° elevation angle, at 0114:51 UTC 19 May 2010, from the same location as for Fig. 6. Range rings shown every 1 km.

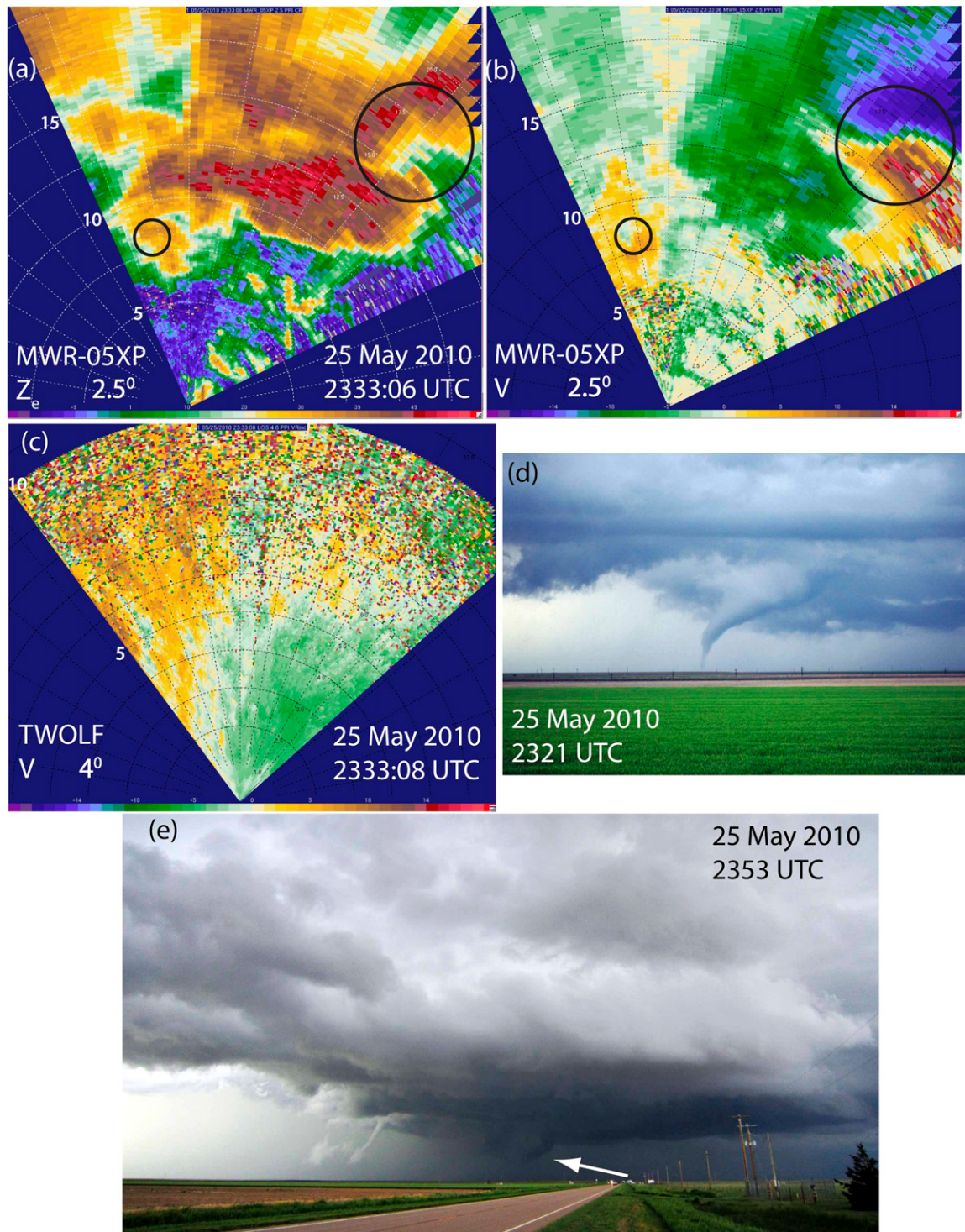


FIG. 8. Storm-scale view of (a) equivalent radar reflectivity factor Z_e (dBZ_e) and (b) Doppler velocity V (m s⁻¹) from MWR-05XP, at 2.5° elevation angle, at 2233:06 UTC 25 May 2010, 19.3 km west of Horace, Kansas (or west-northwest of Tribune, Kansas, 3.2 km east of the Colorado border). Range rings shown every 2.5 km. (c) Doppler velocity (m s⁻¹) from TWOLF, at 4° elevation angle, at 2333:08 UTC 25 May 2010. Range rings shown every 1 km. (d) A tornado west-northwest of Tribune and Horace at 2321 UTC 25 May 2010 (courtesy of H. Bluestein). (e) A funnel cloud (associated with a recent tornado) and new wall cloud (white arrow), north-northwest of Tribune at 2353 UTC 25 May 2010 (courtesy of H. Bluestein). Black circles indicate locations of cyclonic-vortex signatures in MWR-05XP data.

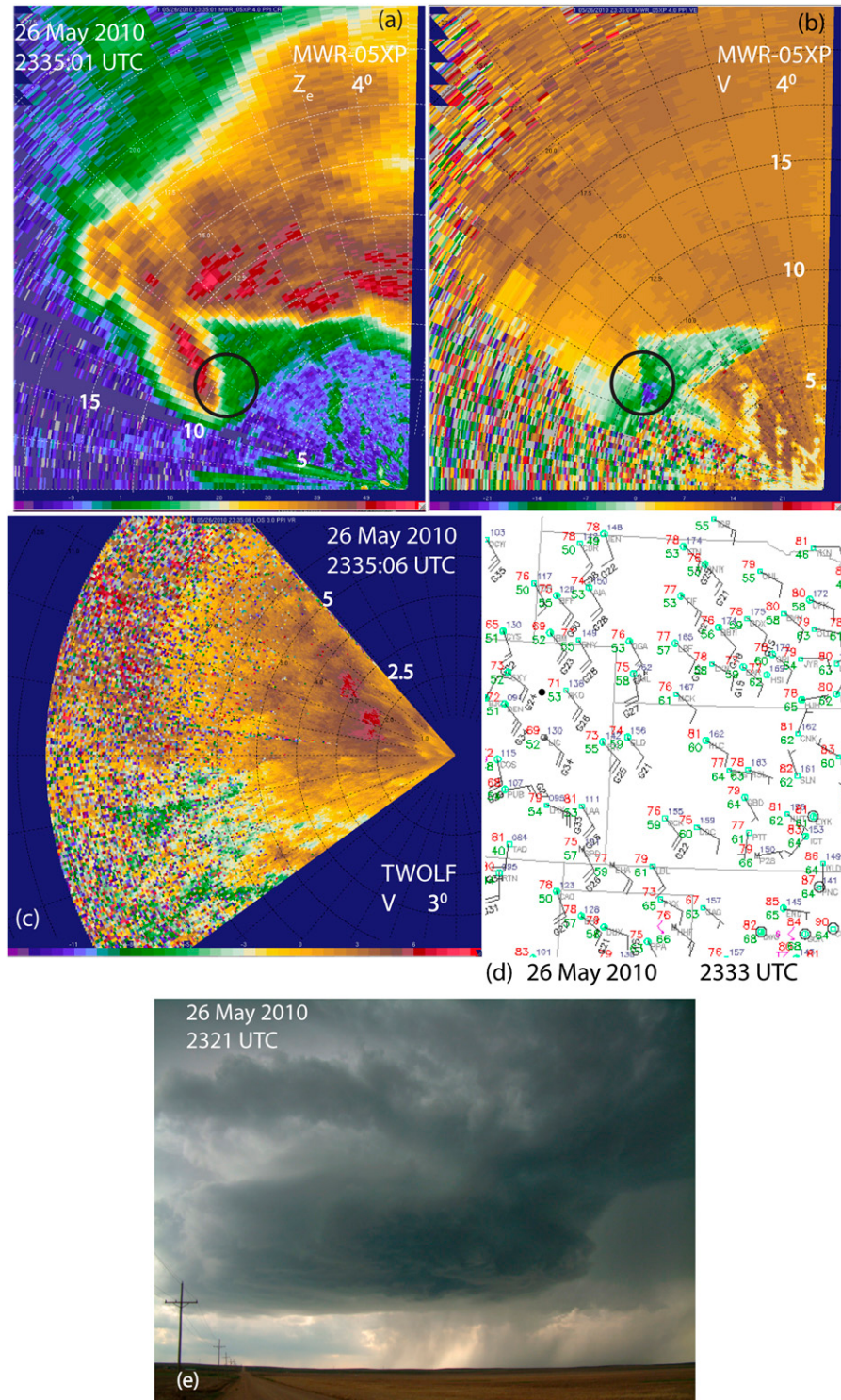


FIG. 9. Storm-scale view of (a) Z_e (dBZ_e) and (b) V (m s⁻¹), from MWR-05XP, at 4° elevation angle, at 2335:01 UTC 26 May 2010, ~12 km south of Wiggins. The black circle marks a divergence signature. Range rings shown every 2.5 km. (c) Doppler velocity (m s⁻¹) from TWOLF, at 3° elevation angle, at 2335:06 UTC 26 May 2010. Range rings shown every 1 km. (d) Surface map, as in Fig. 4d, at 2333 UTC 26 May 2010. The black dot marks the approximate location of TWOLF/MWR-05XP. (e) The supercell base at 2321 UTC 26 May 2010. (Photograph courtesy of J. Houser.)

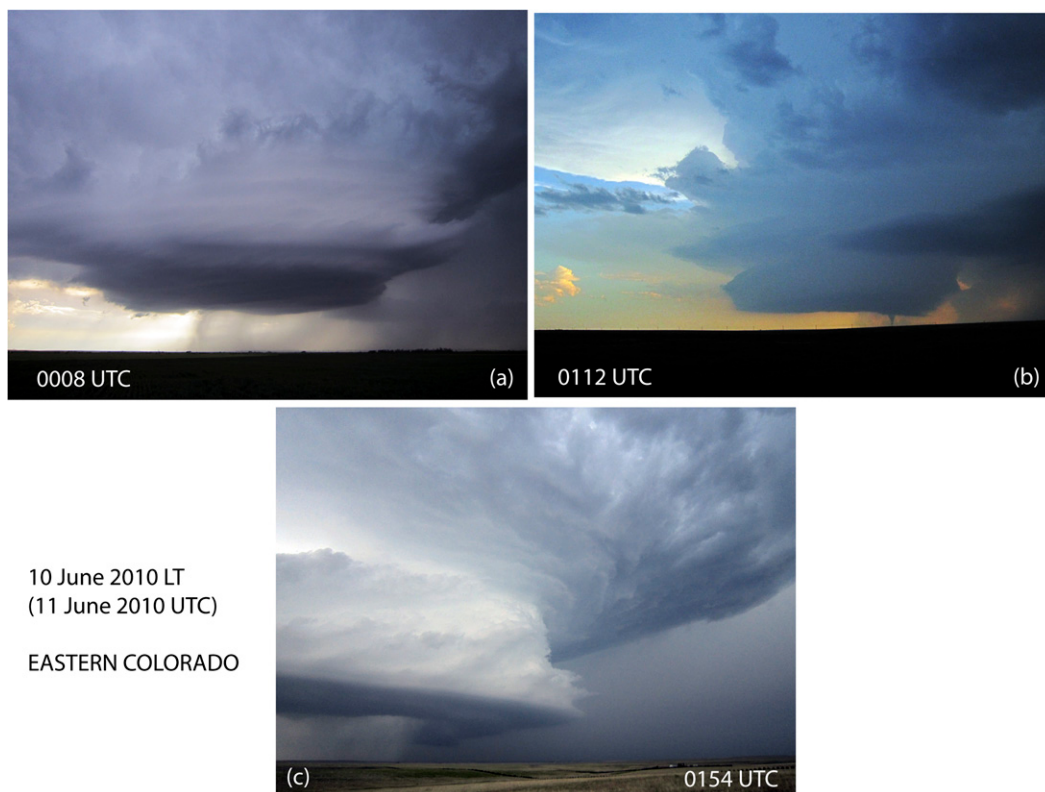


FIG. 10. The supercells in eastern Colorado on 11 Jun 2010 during or approximately when radar and lidar data were being collected. (a) First supercell at 0008 UTC, viewed from the east; (b) second supercell, with a tornado, at 0112 UTC, viewed from the northeast; and (c) second supercell, after the tornado had dissipated, at 0154 UTC; the curved base is to the rear of the surging rear-flank gust front. (Courtesy of H. Bluestein.)

1) GUST FRONT ALONG THE SOUTHERN FLANK OF A DECAYING SUPERCELL

The first deployment was east-southeast of a non-tornadic supercell (Fig. 10a) that had a striated, precipitation-free circular base and precipitation in the background. Radar data and lidar data are discussed to illustrate the passage of a gust front. While a series of scans show the temporal evolution of the gust front passage, the focus in Fig. 11 is on a time after the gust front had passed by. The leading edge of outbound flow (dashed line in Fig. 11b) at 2.5–4-km range seen in MWR-05XP Doppler radar wind data corresponds well with the leading edge of outbound flow and its transition to approaching flow at 3–4-km range in TWOLF Doppler lidar data (Fig. 11c). Evidence of a secondary surge behind the gust front is found as a curved band of enhanced radar reflectivity factor in Fig. 11a and enhanced approaching Doppler velocities (arrow) in Fig. 11b.

2) FLOW AHEAD OF A “HAMMERHEAD” ECHO

MWR-05XP and TWOLF changed deployment location to leave the storm dominated by outflow and to

target a new supercell that had developed to the south and produced a tornado (Fig. 10b) while a deployment site was being sought. The tornado had dissipated by the time the radar and lidar began scanning from the new deployment site, just minutes later. Figures 12–15 illustrate a comparison between the shape of the reflectivity factor appendage on the storm’s right-rear flank, which changed with time, and the flow pattern just to its rear as the storm moved away. The radar reflectivity factor pattern first assumed the shape of the head of a hammer (arrow in Fig. 12a); storm chasers have therefore referred to such a configuration of radar reflectivity colloquially as a “hammerhead echo” (e.g., Lee et al. 2012; Bluestein 2013).

The hammerhead echo was collocated with a maximum in inbound Doppler velocities of $\sim 25\text{--}30\text{ m s}^{-1}$ (Fig. 12b), such that strong cyclonic shear vorticity was present to the north and strong anticyclonic shear vorticity was present to the south. A zone of Doppler velocity convergence was evident ahead of the hammerhead echo (dashed line in Fig. 12) and likely marked the leading edge of the gust front of the supercell. The visual appearance of the leading edge of the supercell (Fig. 10c),

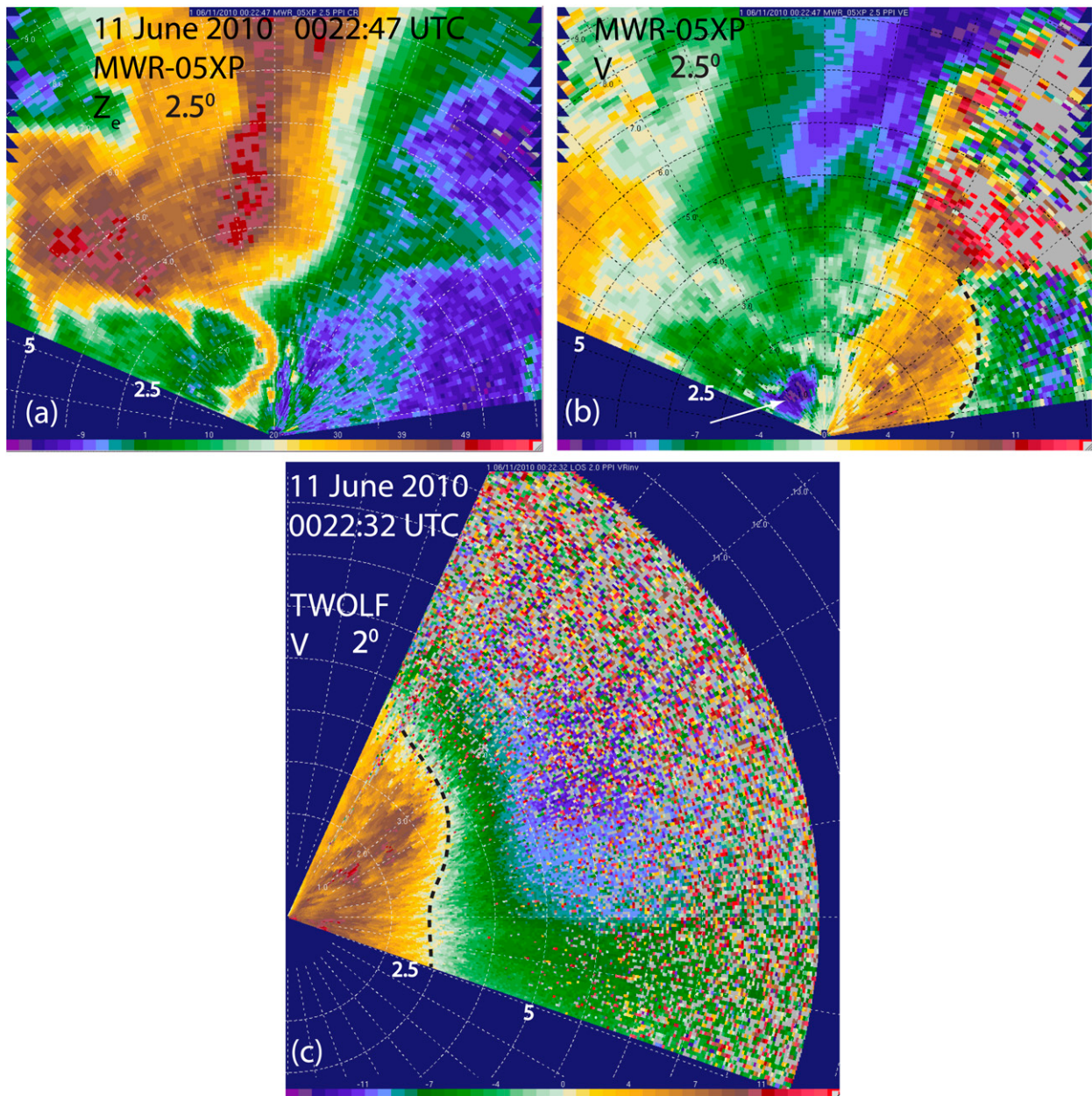


FIG. 11. Storm-scale view of (a) Z_e (dBZ_e) and (b) V (m s^{-1}), from MWR-05XP, at 2.5° elevation angle, at 0022:47 UTC 11 Jun 2010, in a rural area northeast of Byers, Colorado. Range rings shown every 1 km. (c) Doppler velocity (m s^{-1}) from TWOLF, at 2° elevation angle, at 0022:32 UTC 11 Jun 2010. Range rings shown every 1 km. Dashed lines mark the 0 m s^{-1} isodop in a selected area, which are approximately normal to the radial direction and therefore are suggestive of convergence lines.

22 min after the analysis seen in Fig. 12, was that of a curved leading edge with a striated base above. The leading edge of the bulge in the cloud edge was probably associated with the leading edge of the strongest outflow, along the center of the hammerhead echo. TWOLF data were available within $\sim 8 \text{ km}$ of the lidar (Fig. 12c). Within 7-km range, the 0 m s^{-1} isodop was oriented from northwest to southeast, suggestive of a northeast boundary

layer wind. Beyond 7 km, there is some indication of convergence to the northwest, which could be associated with the same convergence line detected at $\sim 7.5 \text{ km}$ range in the MWR-05XP Doppler velocity field (Fig. 12b). There are some narrow bands ($\sim 100 \text{ m}$ in width) in the lidar Doppler (inbound) velocity field to the northeast, within $\sim 3 \text{ km}$ from the lidar. These bands may be manifestations of HCRs. They do not appear to the west, to the

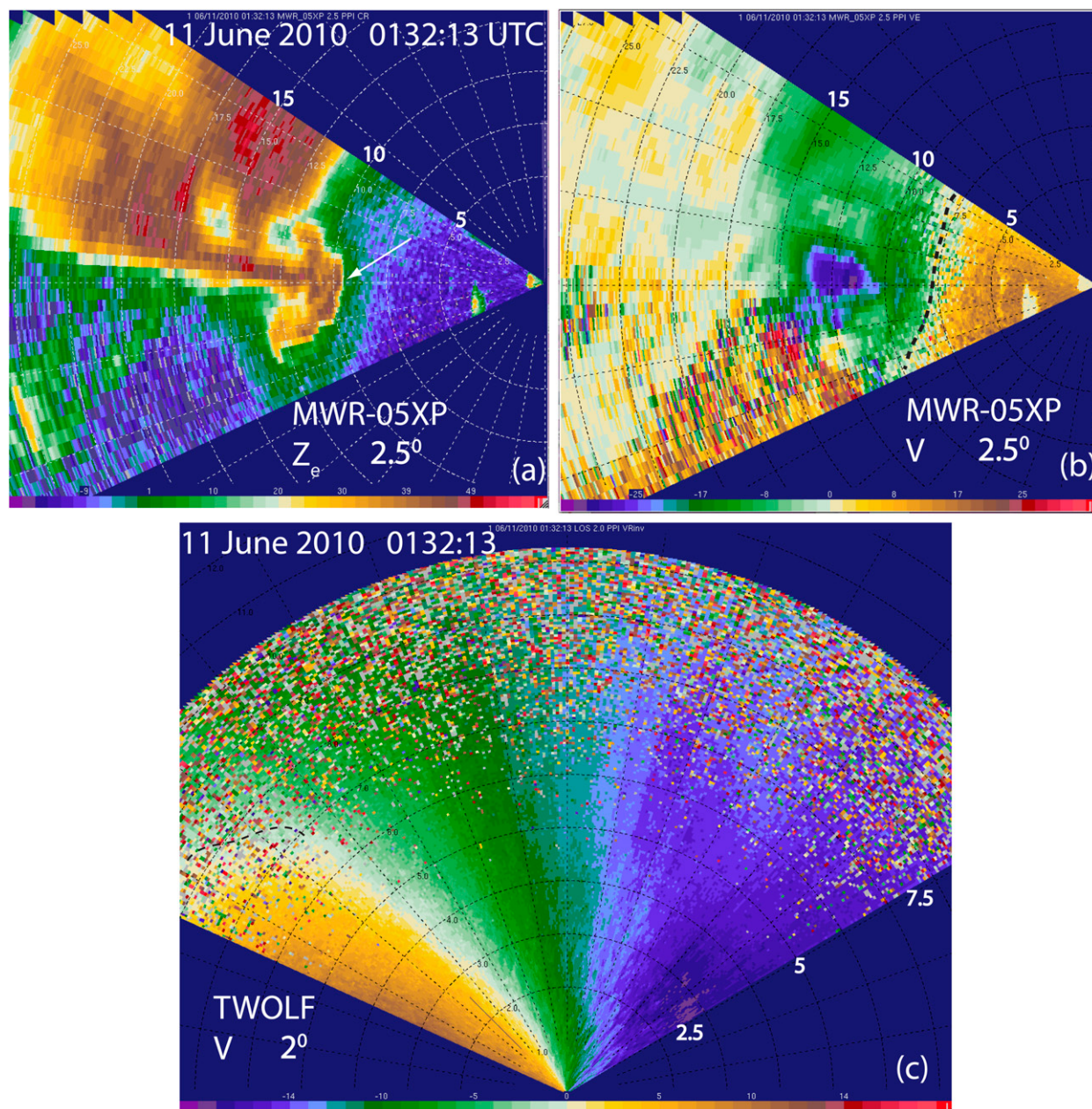


FIG. 12. As in Fig. 11, but at 0132:13 UTC 11 Jun 2010 for both MWR-05XP and TWOLF at 0026:17 UTC, and ~ 35 km north-northeast of Limon or ~ 15 km south of Last Chance, Colorado, south of US 36, just to the east of Route 71. Dashed line marks the 0 m s^{-1} isodop in a selected area, which is approximately normal to the radial direction and therefore is suggestive of a convergence line. Range rings for MWR-05XP are shown every 2.5 km; range rings for TWOLF are shown every 1 km.

rear of the gust front, where the cooler, low-level air is presumably stable and where thermally driven HCRs would not be expected.

As the hammerhead echo approached, there was better opportunity for a comparison between Doppler wind data from MWR-05XP and TWOLF. For example, 6 min later, the hammerhead echo came to ~ 5 km of the lidar (Fig. 13a). At this time the leading edge of the

outflow is evident in both the radar and lidar data (curved line to the northwest, extending from ~ 2 to 4 km in range) (Figs. 13b,c). A 0 m s^{-1} isodop visible to the northeast of the hammerhead echo (dashed line ~ 7 – 8 -km range) is also present in both the MWR-05XP and TWOLF data. The tongue of outbound velocities detected by the lidar (color coded yellow, enclosed by a dashed line, and embedded within a sector of

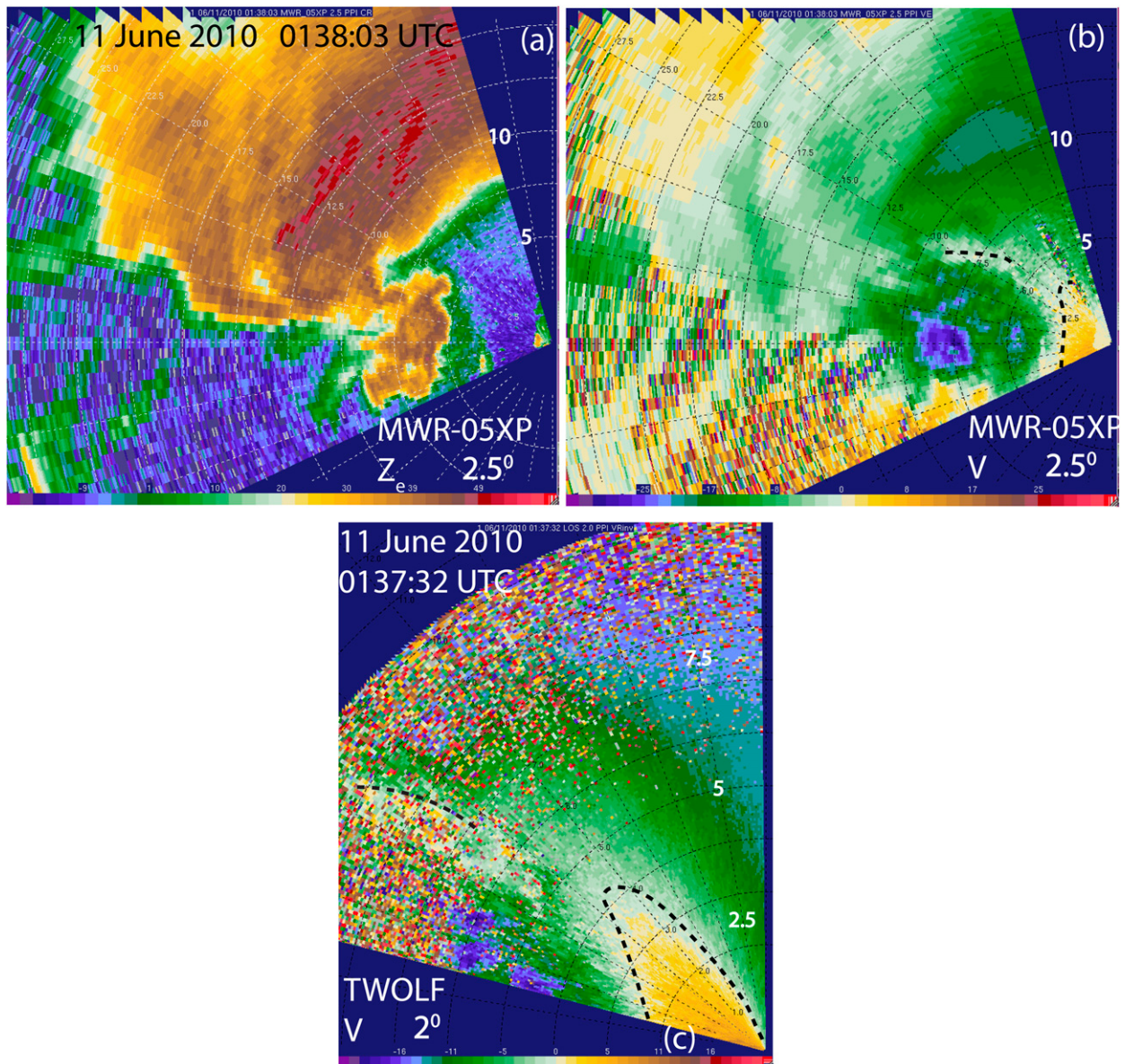


FIG. 13. As in Fig. 11, but at 0138:03 and 0137:32 UTC, for MWR-05XP and TWOLF, respectively; dashed lines in this case highlight the same features in the Doppler wind field seen by both the radar and lidar.

otherwise inbound Doppler velocity) (Fig. 13c) may represent a channel of inflow into hammerhead echo region. Overlap of radar and lidar data complement each other in this case.

3) FLOW SOUTH OF A HOOK ECHO

MWR-05XP and TWOLF then moved to the east to avoid being hit by high winds and by heavy precipitation from the storm and redeployed. By this time, about 15 min later, the hammerhead echo had evolved into a more conventional-looking hook echo, to the north, with a flared back portion on its south side (Fig. 14a),

suggestive of a bulging rear-flank gust front. Ground-clutter contamination precluded Doppler velocity measurements by MWR-05XP within ~ 5 -km range (Fig. 14b). TWOLF data, however, provided an opportunity to map the wind field within 5-km range (Fig. 14c); the data show evidence of convergence along a gust front at ~ 4 -km range to the northwest, and east-northeasterly winds to the north and northeast. The easterly or east-northeasterly winds inferred from the lidar data in Figs. 12c, 13c, and 14c are consistent with the east-northeasterly surface winds reported at Limon, Colorado (not shown), the nearest observing station, to the south.

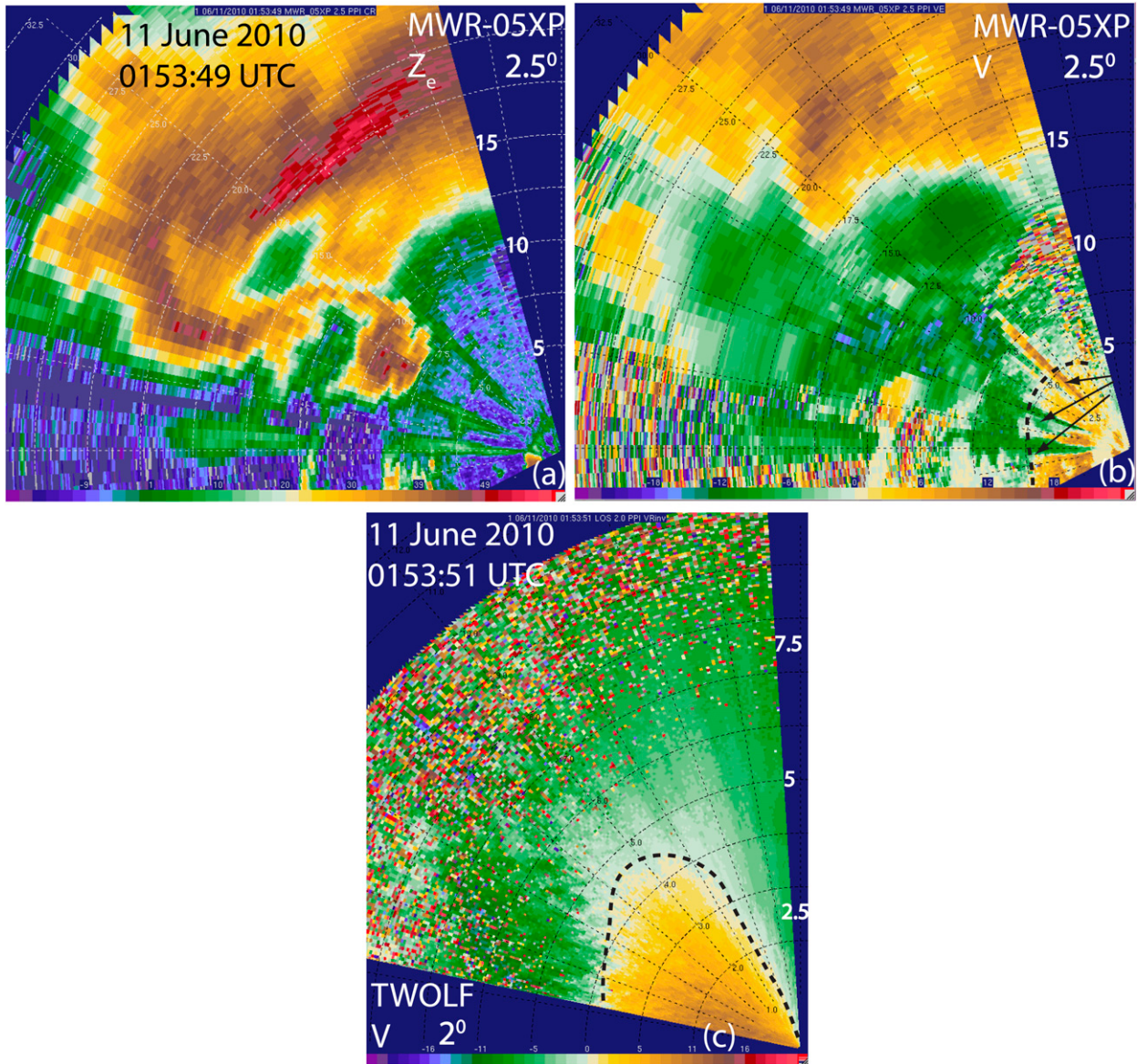


FIG. 14. As in Fig. 12, but at 0153:49 and 0153:51 UTC, for MWR-05XP and TWOLF, respectively, and ~ 16 km east of the previous deployment.

The southeasterly or easterly winds inferred from the lidar data earlier and at another deployment site in Figs. 11c are also consistent with the east-southeasterly winds reported at Limon (not shown).

As the hook echo with a flared-out echo (Fig. 15a) moved to the east and northeast, 13–14 min later, small-scale cyclonic vortex signatures were evident in the MWR-05XP data (Fig. 15b). Within ~ 8 –9-km range, the TWOLF Doppler velocity data (Fig. 15c) looked similar to the MWR-05XP Doppler velocity data (Fig. 15b); however, since the signal returned to MWR-05XP was relatively weak (~ 0 dBZ_e or less), the comparison must

be viewed with extreme caution. The lidar-derived Doppler wind field (Fig. 15c) exhibits considerable finescale structure, perhaps associated with turbulent flow behind the gust front.

4. Summary and suggestions for future field programs

a. Summary

It was found (Figs. 6–9, 14) that lidar data *complemented* radar data by providing coverage of the Doppler wind field within ~ 5 km of the radar, where

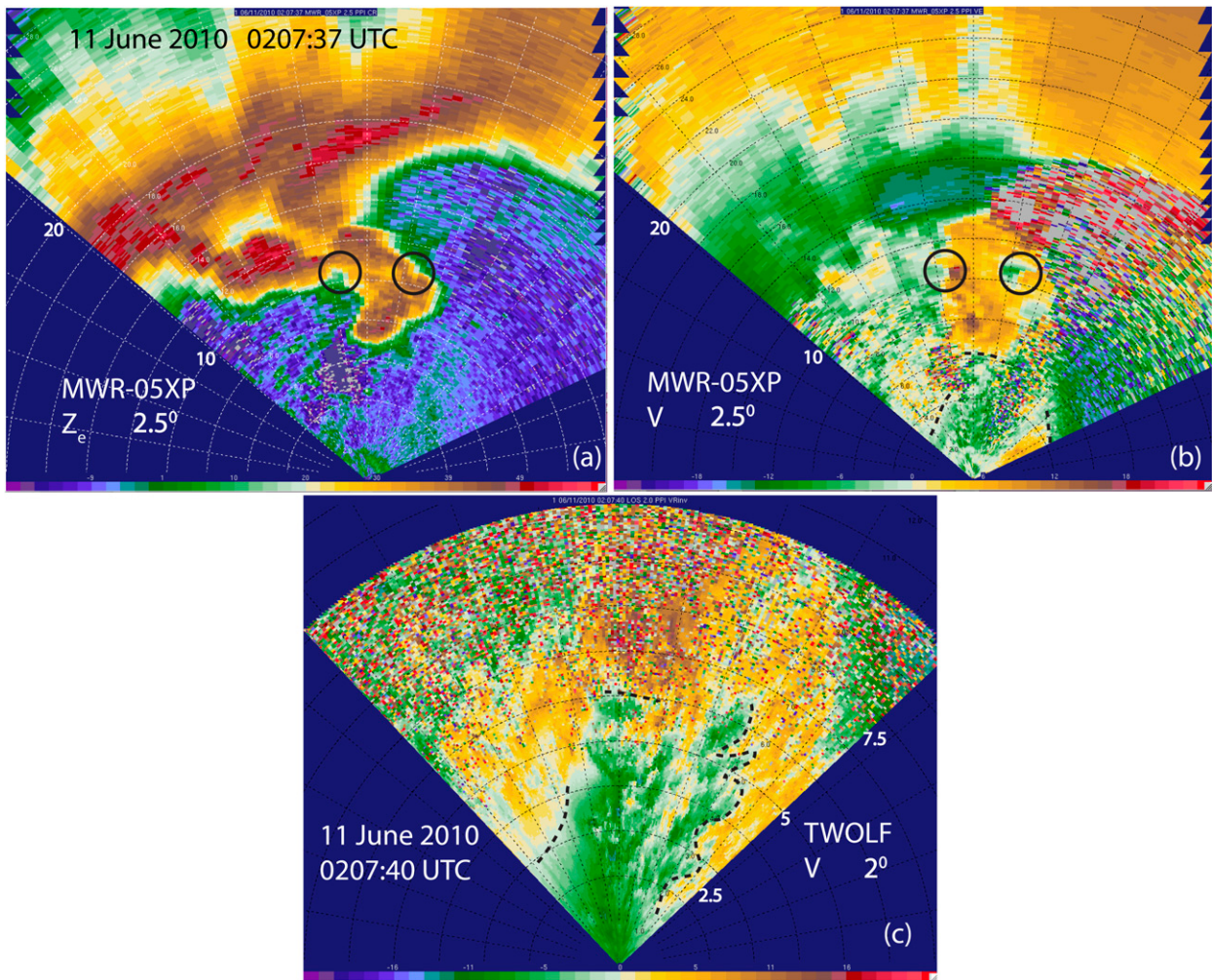


FIG. 15. As in Fig. 13, but at 0207:37 and 0207:40 UTC for MWR-05XP and TWOLF, respectively, and range rings for MWR-05XP shown every 2 km. Circles mark locations of cyclonic vortex signatures.

ground clutter often contaminated MWR-05XP observations in clear air, most likely owing to the relatively broad beam of the MWR-05XP. While ground clutter could be mitigated, the scanning rate of the radar would have to be slowed down to increase the dwell time; to do so would take too much time, thus cancelling the rapid-scan capabilities of the radar (Bluestein et al. 2010). For the cases in which ground-clutter contamination was not particularly evident, both the MWR-05XP and TWOLF were able to measure similar wind fields (Figs. 11–13), both when the wind field was relatively homogeneous³ (Fig. 12) and when a convergent boundary was present (Figs. 11, 13). In many instances, tornadoes

were intercepted at 10-km range or beyond, well beyond the range of TWOLF. The importance of getting MWR-05XP and TWOLF within ~ 5 km of tornadoes is therefore emphasized if successful observations are to be made.

On the other hand, observations in the clear-air boundary layer upstream from supercells were relatively easy to make. In some instances streaks and bands in Doppler velocity suggestive of HCRs were observed. There was no correlation, for the limited number of cases obtained, between the appearance of HCRs or their orientation and tornadogenesis.

Vertical cross sections parallel to the low-level wind or at a relatively small angle from it were particularly useful for observing the finescale vertical structure of the wind field (Fig. 5; cross sections through gust fronts were also useful, but not shown because they are not novel).

³ At least at close range. There was a boundary, but it was beyond the range of the lidar.

It is therefore concluded that the addition of a mobile Doppler lidar to a mobile Doppler radar mounted on the same platform is a valuable addition by 1) allowing for continuous Doppler wind coverage from the radar/lidar in clear air up to the precipitation region of a storm when the closest edge of the storm is about 5–10 km away and 2) providing vertical cross sections of Doppler velocity that reveal the finescale structure in the boundary layer in clear air (Fig. 6).

b. Suggestions for future field programs

Based on our field program in 2010, it is suggested that the following improvements should be considered for future field experiments:

- 1) The scanning rate needs to be increased so that volume scans can be collected, within 90° – 120° sectors, over a period not exceeding 1 min. At the current slow scanning rate, it takes ~ 30 s just to scan one 90° sector at one elevation angle. Increasing the scanning rate without sacrificing spatial resolution will require faster processing in real time. The maximum possible mechanical scanning rate is $\sim 30^{\circ} \text{ s}^{-1}$.
- 2) The range resolution of the lidar should be increased from ~ 50 m to the best technically possible so that the range resolution can better match the azimuthal resolution. While the LMCT lidar system cannot do this, other laser systems can achieve ~ 20 – 30 -m resolution (e.g., Grund et al. 2001; Pearson et al. 2009).
- 3) The truck should be deployed as close to the feature being scanned as possible or if from a more considerable (e.g., >10 km) distance, just ahead and to the right of, the projected path of the feature. The lidar's range in the plains turned out to be ~ 5 – 10 km. The maximum range achieved by TWOLF has been 27 km in the boundary layer elsewhere during another experiment. With an improved data system, data could be collected and processed out to farther ranges than those attained during VORTEX2, perhaps out to ~ 30 km. Like the University of Massachusetts' W-band, mobile, Doppler radar (Bluestein et al. 2007b), TWOLF must be placed close to the feature of interest and not with any heavy intervening precipitation. Thus, there is an additional burden not faced with mobile, X-band Doppler radars. Since the half-power beamwidth of the MWR-05XP is approximately twice that of most mobile, X-band Doppler radars, getting very close will increase the spatial resolution of the radar data to that of other radars at longer ranges. One limitation of getting close is the setup time, which must not be too long or deployments will be too

short, especially when the meteorological target is translating rapidly.

- 4) The lidar system's center frequency must shift automatically to allow for a range of Doppler velocities of $\pm 130 \text{ m s}^{-1}$ and to allow for successful data collection in the strongest tornadoes. This capability has been partially demonstrated, but the data-processing software has not been modified yet to implement it. For this procedure, the center frequency is shifted in 50-MHz increments every 200 ms between -100 and $+100$ MHz relative to the nominal zero velocity reference frequency of 805 MHz; thus, there is overlapping coverage of $\sim \pm 100 \text{ m s}^{-1}$, to account for all but the most intense tornadoes, in which wind speeds have been measured by mobile Doppler radars as high as 120 – 135 m s^{-1} (e.g., Pazmany et al. 2013). In the future, a more state-of-the-art Doppler lidar system could be used in which aliased data can be dealiased using conventional methods.
- 5) It is often difficult to find a level and safe site for deployments. One must be careful to orient the truck so that it mostly faces in the direction of the meteorological feature to be probed, in order that the phased-array antenna from MWR-05XP does not block the lidar beam from TWOLF.
- 6) The truck platform must be leveled so that spatial information is precise. By ensuring a ground hit during every RHI, the elevation angle could be known exactly. The radar and lidar are currently being installed on a new truck with a leveling system.

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