Observations of Quasi-Symmetric Echo Patterns in Clear Air with the CSU–CHILL Polarimetric Radar

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ABSTRACT

On a few occasions during the summer and fall of 2002, and again in the fall of 2003, the Colorado State University (CSU)–University of Chicago–Illinois State Water Survey (CHILL) S-band polarimetric Doppler radar observed dumbbell-shaped radar echo patterns in precipitation-free air returns. Dumbbell shaped refers to two distinct and quasi-symmetrical regions of echo surrounding the radar. These were horizontally widespread (thousands of square kilometers) layers, with the highest reflectivity factors (sometimes $>$20 dBZ) arranged approximately perpendicular to the direction of the mean wind. The echoes coincided with strongly positive differential reflectivity (Z_{DR}) measurements (often $>$4 dB). Most interestingly, the echoes were elevated near the top of the boundary layer in the 2–3-km-AGL vertical range. Assuming a horizontally uniform layer of scatterers, the observations suggest that targets aloft are quasi prolate in shape and aligned horizontally along the direction of the mean wind. The echoes tended to occur on days when nocturnal inversions persisted into the following day, and solenoidal-like circulations (easterly upslope near the surface, and westerly flow aloft) existed. In some cases, the echoes exhibited diurnal behavior, with dumbbell-shaped echoes only occurring during the day and a more azimuthally uniform echo at night. On occasion, the echoes were coincident with the occurrence of widespread smoke from nearby forest fires. It is suggested that these echoes, which are rare for the CSU–CHILL coverage region, were caused by insects flying in a preferred direction, with the trigger for the migration being either the forest fires or oncoming winter. The local meteorological conditions likely affected the structure of these echoes.

1. Introduction

Insects have been observed since the very early days of radar because they cause significant radar backscatter at most meteorological radar wavelengths. An early example of echoes attributed to insects is Browning and Atlas (1966). Typically, such echoes fill the mixed boundary layer, with their intensity decreasing with height (e.g., Wilson et al. 1994). Oftentimes, elevated insects occur within narrow boundary layer updrafts (Achtemeier 1991), which often are associated with radar ''fine lines'' (e.g., Doviak and Zrnic 1993; Russell and Wilson 1997). In addition, insects can fly in narrow vertical layers situated well above the ground (Drake 1985a,b; Chapman et al. 2003).

The availability of dual-polarization radar greatly improved the identification of insect echoes, mainly through the use of differential reflectivity (Z_{DR}), a measure of the reflectivity-weighted mean axis ratio (Seliga and Bringi 1976). The mathematical definition of differential reflectivity is $Z_{DR} = 10 \log_{10} (Z_H/Z_V)$, where Z_H is the reflectivity factor from the horizontally polarized transmitted and received radiation, and Z_V is the reflectivity factor using vertical polarization. Insects normally have larger cross sections in the horizontal compared to the vertical, leading to very large Z_{DR} values (up to $+$10 dB or more; Riley 1985; Vaughn 1985; Zrnic and Ryzhkov 1998). Indeed, the large Z_{DR} values from insects allow them to be distinguished from birds, whose size and shape tend to cause lower values (typically from -1 to $+3$ dB; Zrnic and Ryzhkov 1998).

A population of insects flying in a preferred direction will have the appearance of dumbbell-shaped regions of enhanced horizontally polarized radar reflectivity factor (Z_H) and Z_{DR}. Dumbbell shaped refers to two distinct and quasi-symmetrical regions of echo surrounding the radar. This result is because the horizontal radar cross

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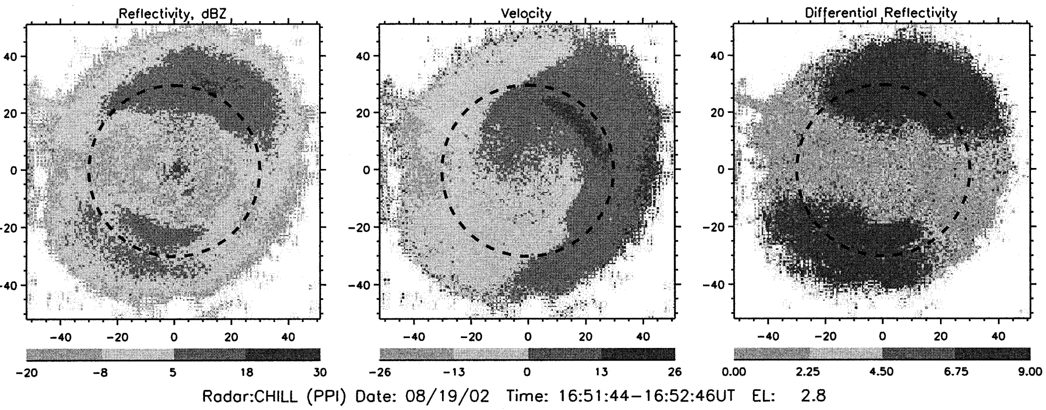

FIG. 1. PPIs of (left) Z_H, (middle) radial velocity, and (right) Z_{DR}, for elevation 2.8° at 1651 UTC (1051 LT) 19 Aug 2002. Distances (km) are relative to CSU–CHILL. The 30-km range ring is shown by the dash circle.

section (σ_H) of the insects along the direction of travel will be reduced. On the other hand, σ_H will be maximized when viewed perpendicular to the travel direction. Note that, under these circumstances, the vertical reflectivity factor Z_V should not change with the azimuth. Indeed, dumbbell-shaped radar echoes have been observed before, with insects traveling in a preferred direction (Riley 1975; Schaefer 1976; Mueller and Larkin 1985). Such observations are common in the southeastern United States [D. Zrnic, National Oceanic and Atmospheric Administration (NOAA)/National Severe Storms Laboratory (NSSL) 2003, personal communication], but were heretofore unnoticed in the Colorado State University (CSU)–University of Chicago–Illinois State Water Survey (CHILL) S-band polarimetric Doppler radar coverage region in northeastern Colorado.

However, on a few occasions during the summer and fall of 2002, and again in fall 2003, the CSU–CHILL radar observed precisely such a phenomenon. On these days, multiple plan position indicator (PPI) volume scans were made of temporally persistent and horizontally widespread (thousands of square kilometers) dumbbell-shaped echoes confined within a narrow vertical layer well above the surface (2–3 km AGL). The highest Z_H values (sometimes >20 dBZ) were arranged approximately perpendicular to the direction of the mean wind as provided by radial velocity data. This paper discusses these observations of insects flying in a preferred direction and offers some potential explanations for why such a rare event (for the CSU–CHILL's location) occurred, and how local meteorological patterns may have played a role in the observed echo structure.

2. Radar observations

Figures 1 and 2 show a series of PPIs and range–height indicators (RHIs), respectively, from the CSU–CHILL radar after 1600 UTC [1000 local time (LT)] 19 August 2002. In these figures, note how the major regions of enhanced Z_H and Z_{DR} were approximately centered on the zero radial velocity curve. The Z_{DR} values were so positive, in fact, that they overwhelmed the data-processing algorithm at CSU–CHILL, which is de-

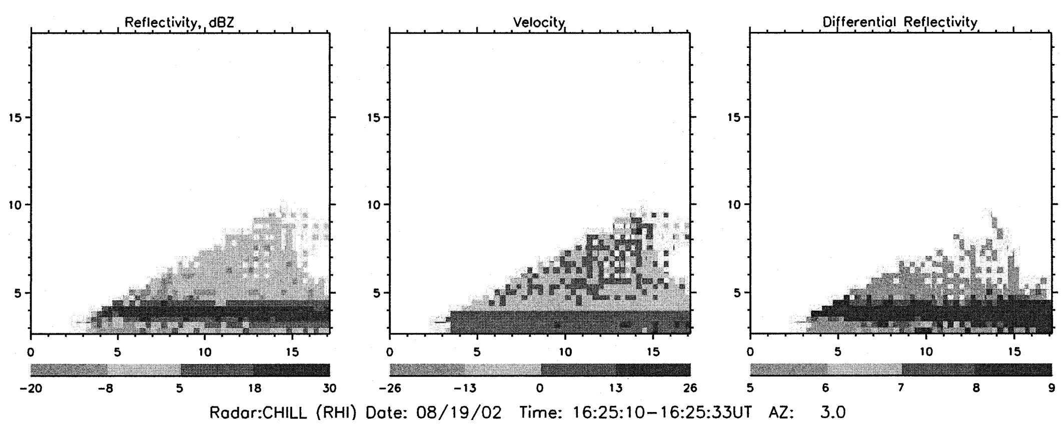

FIG. 2. RHIs of (left) Z_H, (middle) radial velocity, and (right) Z_{DR}, for azimuth 3.0° at 1625 UTC (1025 LT) 19 Aug 2002. Horizontal distance (km) is relative to CSU–CHILL. Vertical distance is in km MSL (CSU–CHILL is at 1.4 km MSL, so subtract 1.4 to get km AGL).

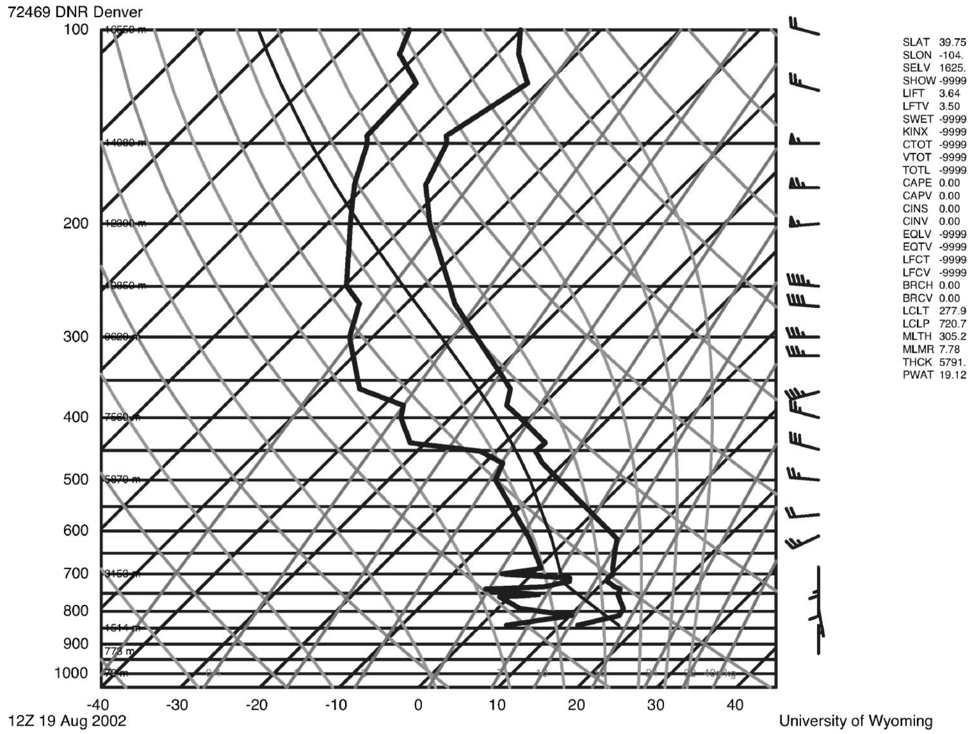

FIG. 3. Skew *T*–log*p* plot for the 1200 UTC (0600 LT) sounding from Denver on 19 Aug 2002.

signed for higher-resolution Z_{DR} values typical of precipitation echoes (approximately from -1 to $+5$ dB). Due to dynamic range considerations for the Z_{DR} measurements, no information was available above approximately 9 dB. Maximum Z_{DR} values likely were higher. Along the upper-level wind axis, however, there was a much weaker signal. In the RHIs (Fig. 2), it is apparent that the echoes were elevated, in the range 1.5–3 km AGL, relative to CSU–CHILL (located at 1432 m MSL). Both the radial velocity observations and the Denver, Colorado, sounding from 1200 UTC (0600 LT) that morning (Fig. 3) indicated that this was a layer of significant vertical wind shear, with southerly flow below and westerly flow aloft. The sounding also indicated that this vertical layer contained very stable air. Overall, it appears that the radar targets were located in a stable region near the top of the boundary layer.

Observations qualitatively similar to those of 19 August were made on 9 and 17 October 2002. Once again, on these days, the CSU–CHILL radar observed dumbbell-shaped echoes oriented perpendicular to the mean wind (Figs. 4 and 5). However, Z_H and Z_{DR} values were lower than on 19 August, though maximum Z_{DR} values still were well above 4 dB, often approaching 9 dB. The vertical location of these echoes was again elevated near the top of the boundary layer, in the 2–3-km-AGL range.

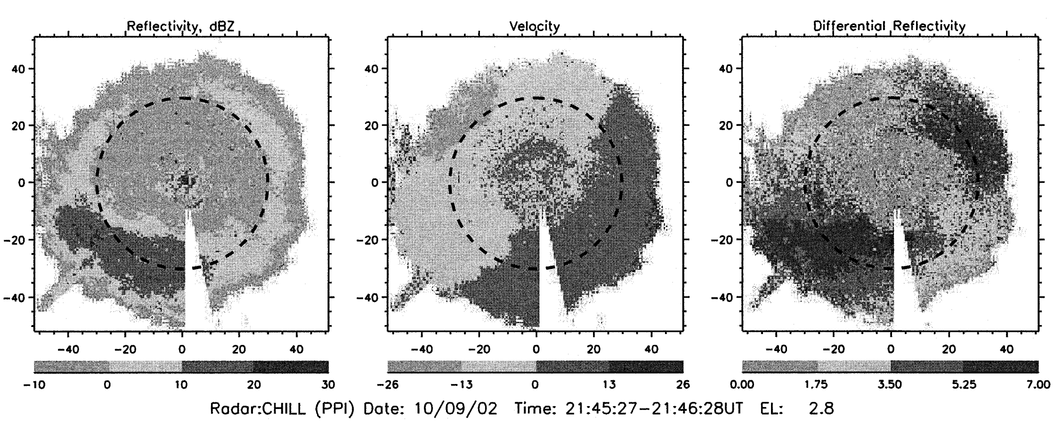

FIG. 4. Same as Fig. 1, but for 2145 UTC (1545 LT) on 9 Oct 2002.

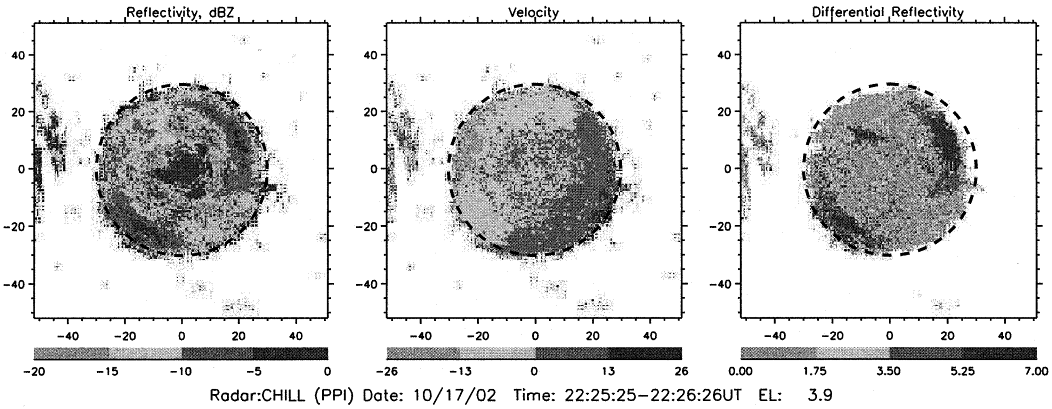

FIG. 5. Same as Fig. 4, but for elevation 3.9° at 2225 UTC (1625 LT) 17 Oct 2002.

There was notable asymmetry in the 9 October echoes, with the southwest echo much stronger than that of the northeast. The echoes were much weaker on 17 October, although the dumbbell-shaped pattern still was visible.

On all days in 2002 (including 19 August), the radar echoes were temporally persistent, lasting for several hours in some cases. On 19 August, the north–south-arranged dumbbells gradually shifted east over the 1600–2300 UTC time frame (CSU–CHILL commenced scanning after 1600 UTC, or 1000 LT), and the southern dumbbell gradually weakened in echo strength. In the last couple of hours (2100–2300 UTC, 1500–1700 LT), widespread convection began, rendering the northern dumbbell indiscernible. On 9 October, the dumbbell-shaped echoes were persistent with little structural evolution for the entire time the radar was scanning, approximately 1730–2230 UTC (1130–1630 LT). On 17 October, the radar was run only for about 1.5 h, from 2130 to 2300 UTC (1530–1700 LT), and during this time the echoes underwent minimal evolution.

Interestingly, all 3 days also coincided with nearby forest fires. On 19 August visual observations indicated a faint but widespread midlevel haze associated with the Mount Zirkel Complex forest fire near Steamboat Springs, Colorado (>200 km west of CSU–CHILL). This fire had burned approximately 30 000 acres by this time (CIDI 2004). Imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board the National Aeronautics and Space Administration (NASA) *Terra* satellite (not shown) indicated advection of the smoke plumes from this large fire toward the CSU–CHILL coverage region. On 9 and 17 October there were prescribed burns in Pingree Park (~60 km west-northwest of CSU–CHILL), although these fires were only a few dozen acres in size (CIDI 2004). On 9 October there was widespread haze due to this fire, whereas on 17 October there was less haze but a visible smoke plume. The presence and location of these October fires were confirmed by MODIS Active Fire Detection data. In fact, there were in situ penetrations of the 17 October smoke plume by the National Center for Atmospheric Research (NCAR) C-130 as part of the Instrument Development and Education in Airborne Science, Phase 2 (IDEAS-2) project.

There is no evidence for or against multiday persistence of the August dumbbell-shaped echoes. There was no scanning between 8 and 19 August, and scanning after 19 August began after the onset of widespread convection, which would have disrupted insect movements through gust fronts and the like. Indeed, that was the likely explanation for the eventual dissipation of the pattern on 19 August. There was an apparent dumbbell-shaped pattern when the radar was run for less than 1 h on 7 October 2002, on which day there was no known fire in the Rocky Mountain region (CIDI 2004). The echo structure was similar to that of 9 October. No scanning was performed on 8 October or 1 week prior to 7 October, and the next scanning day beside 9 October was 14 October, so multiday persistence of this pattern could not be confirmed. On 14 and 15 October there were some faint hints of a dumbbell-shaped echo pattern, particularly in Z_{DR} in CSU–CHILL's southwest quadrant, but these days were weak even by 17 October standards, and there was no obvious pattern on 16 October (no scanning occurred after the 17th until the 22d).

Clear evidence of a multiday event came when dumbbell-shaped echoes occurred again during a few days in late September 2003. CSU–CHILL was operated for other reasons on 22 September and observed the classic dumbbell-shaped pattern once again, this time with peak Z_H values in the high teens and Z_{DR} values once again at the 9-dB limit (not shown). Local Next Generation Weather Radar (NEXRAD) imagery was examined, and it was discovered that these dumbbell-shaped echoes were prevalent throughout the Front Range and beyond, from Pueblo, Colorado, north to Cheyenne, Wyoming, and as far east as Goodland, Kansas.

An example of the evolution of these patterns is provided by Denver NEXRAD (KFTG) imagery in Fig. 6. The dumbbells evolved from a more uniform pattern

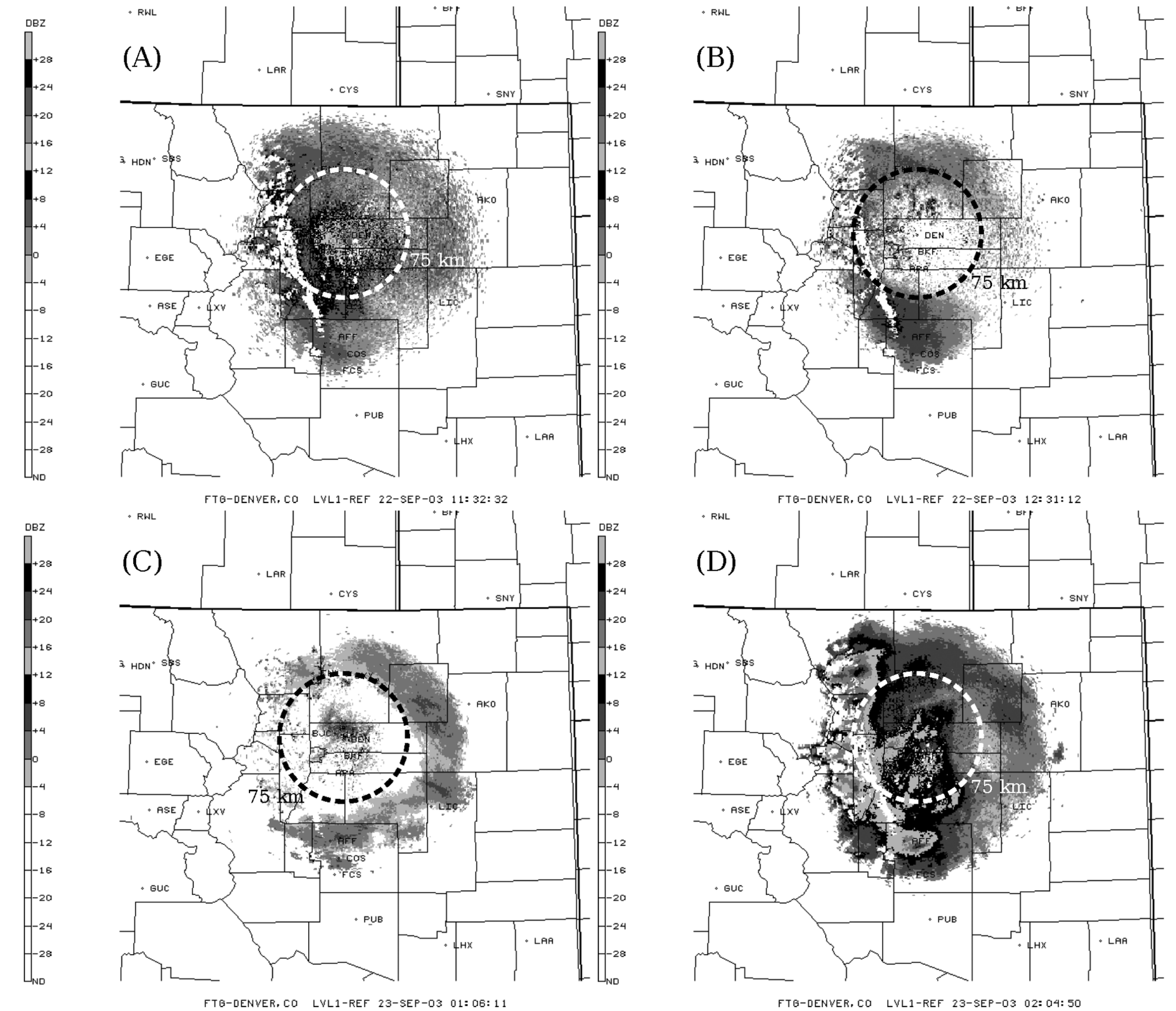

FIG. 6. Base scan radar reflectivity factor imagery from the Denver NEXRAD radar (KFTG), at four different times on one day: (a) 1132 UTC (0532 LT, presunrise) 22 Sep 2003, (b) 1231 UTC (0631 LT, postsunrise) and (c) 0106 UTC (1906 LT, presunset) 23 Sep 2003, and (d) 0204 UTC (2004 LT, postsunset). NEXRAD imagery courtesy of NCAR. The 75-km range ring is indicated by the dashed circle.

surrounding the radar right before local sunrise (sunrise at ~1245 UTC, 0645 LT; Figs. 6a–b). This pattern gradually shifted eastward, and by the end of the day the dumbbells had merged into an arc surrounding the eastern domain of the Denver NEXRAD (Fig. 6c). Later, by 1 h after sunset (sunset at ~0100 UTC on 23 September, or 1900 LT on 22 September), the more uniform pattern had returned (Fig. 6d). This diurnal evolution was apparent in NEXRAD data on 21 and 23 September as well, although 22 September had the most well-defined dumbbell-shaped echoes. Photographs and visual observations on these days indicated mostly clear skies and no precipitation. There was a small fire near Fort Collins, Colorado, late in the day on 23 September, but no reported fires near the CSU–CHILL coverage region prior to then.

3. Nature of the radar targets

Based on arguments outlined in the introduction, we hypothesize that the observed dumbbell-shaped echoes are consistent with the presence of horizontally aligned, prolate-shaped particles. To investigate the plausibility of this inference, electromagnetic scattering calculations were made using a T-matrix model (Waterman 1965) and were compared to the 2002 cases. Assuming that the targets are oriented in a specific horizontal direction, and using an arbitrary size distribution (with targets contained within the Rayleigh regime at S band), good agreement in the azimuthal variation of Z_H and Z_{DR} between the observations and the model is obtained, particularly for the strongest echo day (19 August 2002; Fig. 7). Note that no attempt was made to match specific

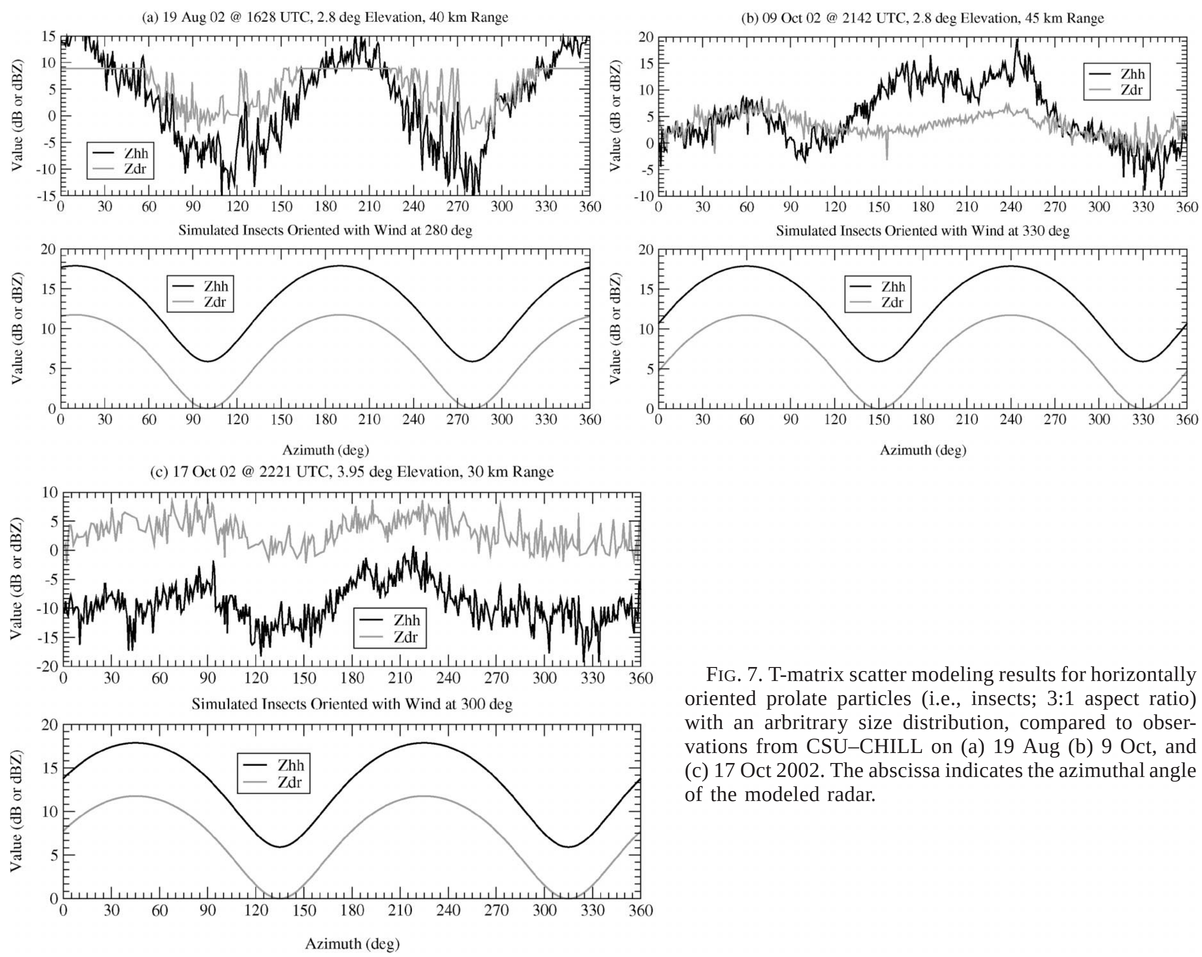

FIG. 7. T-matrix scatter modeling results for horizontally oriented prolate particles (i.e., insects; 3:1 aspect ratio) with an arbitrary size distribution, compared to observations from CSU–CHILL on (a) 19 Aug (b) 9 Oct, and (c) 17 Oct 2002. The abscissa indicates the azimuthal angle of the modeled radar.

Z_H and Z_{DR} values between the model and observations, which would require information on the actual size distribution of the scatterers, which was unavailable. More certain is how Z_H and Z_{DR} should vary in azimuth for aligned prolate-shaped particles, because this is not as affected by the size distribution.

There is some mismatch in specific peaks and valleys of the Z_H curves on 9 October, suggesting a partial breakdown either in the assumption of uniformity in spatial distribution, or in the assumption of aligned prolate-shaped scatterers within the Rayleigh regime. However, the Z_{DR} variations match well, so we do not believe departures from the theoretical assumptions are severe enough to invalidate the basic inference of aligned prolate-shaped particles on this day. The amplitudes on 17 October are weak but azimuthal variability is still a good match, again supporting our inference.

Based on the scatter modeling along with the previous work on insect echoes that was outlined in the introduction, the most likely explanation for the dumbbell-shaped echoes is that they were caused by insects traveling in a preferred direction. The targets are not likely to be birds because the observed Z_{DR} values are too high in every case (Zrnic and Ryzhkov 1998).

4. Discussion

As mentioned before, the vertically elevated dumbbell-shaped echo pattern was heretofore unnoticed at the CSU–CHILL radar despite years of operation in northeastern Colorado. This does not mean that such a pattern never occurred in the past, because it could have been scanned but not noted, or it could have occurred when the radar was not run, but it most definitely is rare based on the experience of scientists and staff involved with the radar. Thus, some explanation of the reason for its occurrence is in order.

Given the temporal and spatial proximity of the dumbbell-shaped echo pattern to forest fires on many of the studied days, the fires may have influenced insect behavior enough to cause the observed pattern. For example, the insects could have been buoyed aloft by thermals, perhaps as a result of the nearby fires, explaining the temporal proximity between the echo patterns and the fires. Lofting of insects by updrafts has been studied via radar by Achtemeier (1991).

Another intriguing possibility is that the insects sensed the fires or smoke plumes, and then attempted to travel upwind toward them. Certain species of insects are known to react to forest fires and infest burned trees, sometimes even as the trees are still smoking (e.g., McCullough et al. 1998; Suckling et al. 2001). Due to the stable layer, the shallow vertical region where the westerly winds were strongest would contain most of the smoke the fire-heated air that would be advected over the eastern plains. Thus, it would contain the necessary attractants for insects that infest burned forests.

However, it should be noted that the some or all of the insect observations may be due to an entirely different reason than the fires. The data from the September 2003 event, which was not associated with nearby fires, show that the dumbbell-shaped echoes can be diurnally driven, with the insects traveling in a preferred direction within a higher-altitude band only during the day, and not headed in a uniform direction during nighttime (as well as being more spread out vertically). One plausible explanation in this case is that insects may have been leaving the mountains to the warmer environs of the plains. That also could be an explanation for the October 2002 migration.

A diurnally driven solenoidal circulation may be a factor in the occurrence of these dumbbell-shaped echoes. As described by Tripoli and Cotton (1989), the solenoid would be defined by an easterly upslope flow near the surface and a westerly return flow above the inversion level. The inversion is important in this scenario, because it confines the two flows to their respective vertical layers. All known dumbbell-shaped echo days were characterized by residual nocturnal inversions (e.g., Fig. 3), strong westerly flow above the inversion, and some component of easterly flow near the surface (visible in low-elevation radar scans; not shown). Such a circulation pattern would present two distinct flow regimes, favoring eastward travel aloft and westward travel near the surface. Insects attempting to travel eastward would have an easier time flying aloft during the day, whereas at night when the low-level upslope was replaced by drainage flows off the mountains there would be less impetus to exist in a shallow vertical layer aloft. This may explain the observed diurnal echo behavior in late September 2003.

Note that this solenoid explanation requires an initial trigger for the migration, for example, forest fires or oncoming winter, because these meteorological conditions are far more common than dumbbell-shaped echo observations by the CSU–CHILL radar. That is, the solenoid does not cause the migration, it simply helps organize it into the observed structure.

5. Conclusions

Combined polarimetric and Doppler data from the CSU–CHILL and other radars were used in concert with atmospheric sounding data to infer the nature of widespread dumbbell-shaped echoes situated near the top of the boundary layer on several days in the summer and fall of 2002, and again in the fall of 2003. The data are consistent with quasi-prolate particles aligned horizontally along the mean wind axis. The observed alignment, vertical distribution, and diurnal activity of the echoes suggests active targets and not passive wind tracers. The observed differential reflectivity values were too large for the targets to be birds (Zrnic and Ryzhkov 1998). Thus, the most plausible explanation for the nature of the targets is that they were insects traveling in a preferred direction.

Although providing a definitive explanation for the observed insect behavior is beyond the scope of this work, some informed speculation has been provided. Our preferred explanation is that the dumbbell-shaped events were due to insect migrations triggered by either nearby forest fires or oncoming winter, and that these migrations were modulated by local meteorological patterns, in particular, a diurnally driven solenoidal circulation. This study provides further evidence that polarimetric radars like CSU–CHILL would be useful tools in examining major insect migration events, along with the interaction between local meteorology and insect behavior.

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