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OBSERVATIONS OF CLEAR-AIR DUMBBELL-SHAPED ECHO PATTERNS WITH THE CSU-CHILL POLARIMETRIC RADAR

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1. INTRODUCTION

On a few occasions during the summer and fall of 2002, the CSU-CHILL S-band polarimetric Doppler radar observed dumbbell-shaped layers of enhanced radar reflectivity factor (Z_H) in clear air (i.e., no precipitation). These were horizontally widespread (1000s of km^2) layers, with the highest Z_H values (sometimes > 20 dBZ) arranged approximately perpendicular to the direction of the mean wind as estimated by Doppler radar methods. The echoes coincided with strongly positive differential reflectivity (Z_{DR}) measurements. The results suggest particles that are quasi-prolate in shape and aligned horizontally along the direction of the mean wind. Though there remains significant uncertainty, it is suspected that these echoes were primarily caused by insects that were lofted to near the top of the boundary layer, perhaps by nearby forest fire plumes.

2. RADAR OBSERVATIONS

Figures 1 and 2 show a series of PPIs and RHIs, respectively, from the CSU-CHILL radar after 16 UTC (10 Local) on 19 August 2002. This was a day when visual observations indicated a widespread but faint mid-level haze likely associated with the Mt. Zirkel Complex forest fire near Steamboat Springs, CO (> 200 km west of CSU-CHILL), which had burned approximately 30,000 acres by this time (NICC Incident Management Reports). Imagery from the MODIS instrument onboard the NASA TERRA satellite indicated advection of the smoke plumes from this large fire toward the CSU-CHILL coverage region.

In these figures, note how the major regions of enhanced Z_H and Z_{DR} are approximately centered on the zero radial velocity zero curve. The Z_{DR} values are so positive, in fact, that they saturated the CSU-CHILL receivers and no information is available above approximately +9 dB. Thus, true Z_{DR} values could be much higher. Along the upper-level wind axis, however, there is much weaker signal. In the RHIs (Fig. 2), it is apparent that the echoes are 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, CO, sounding from 12 UTC that morning (Fig. 3) indicate that this was a layer of significant vertical wind shear, with southerly flow below and westerly flow aloft. The sounding also indicates that a low-level inversion ends in this vertical layer. Overall, it appears that the radar targets are located near the top of the boundary layer.

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Assuming a widespread distribution of targets, the observations suggest particles that are quasi-prolate in shape and aligned horizontally in the direction of the mean wind. This is because Z_H is a measure of the horizontally polarized transmitted and received signal, so the radar cross-section of the particles would be reduced while scanning along the wind axis, and would be maximized while scanning perpendicular to the wind axis. Z_{DR} would be similarly affected since it is a measure of reflectivity-weighted mean axis ratio.

Observations qualitatively similar to 19 August were made on 9 and 17 October 2002. That is, CSU-CHILL observed dumbbell-shaped echoes oriented perpendicular to the mean wind. However, Z_H and Z_{DR} values were lower than on 19 August. Interestingly, both days also saw widespread haze, possibly associated with nearby control burns in Pingree Park (about 60 km WNW of CSU-CHILL), although these fires were only a few dozen acres in size (NICC Incident Management Reports). See Fig. 4 for a photographic example of the haze observed on 9 October.

3. NATURE OF RADAR TARGETS

On all days, the radar echoes were temporally persistent, lasting with little structural evolution for well over an hour in each case (longer radar observations were not made). Because of the high Z_{DR} values, there are two major candidates to explain these unusual clear-air radar observations: smoke and insects.

3.1 *Smoke Hypothesis*

The smoke hypothesis is supported by the temporal proximity of the radar observations to forest fires in the region, as well as the widespread haze observed in some form on all three days. In this case the radar targets would be smoke and ash particles. Indeed, on 19 August some settling of ash onto the ground was observed by persons located within the CSU-CHILL coverage region. Radar observations of smoke and ash particles have been made at S-band (and other frequencies). Some excellent examples are Rogers and Brown (1997), with multiple frequency observations of an industrial fire, and Banta et al. (1992), with Doppler radar and lidar observations of two forest fires. Another example is Fig. 11.36 in Doviak and Zrnic (1993), showing radar-observed smoke plumes over Oklahoma. However, in these and other cases in the literature, the observations are strictly of plumes perhaps a few km wide, and not widespread smoke layers covering 1000s of km^2.

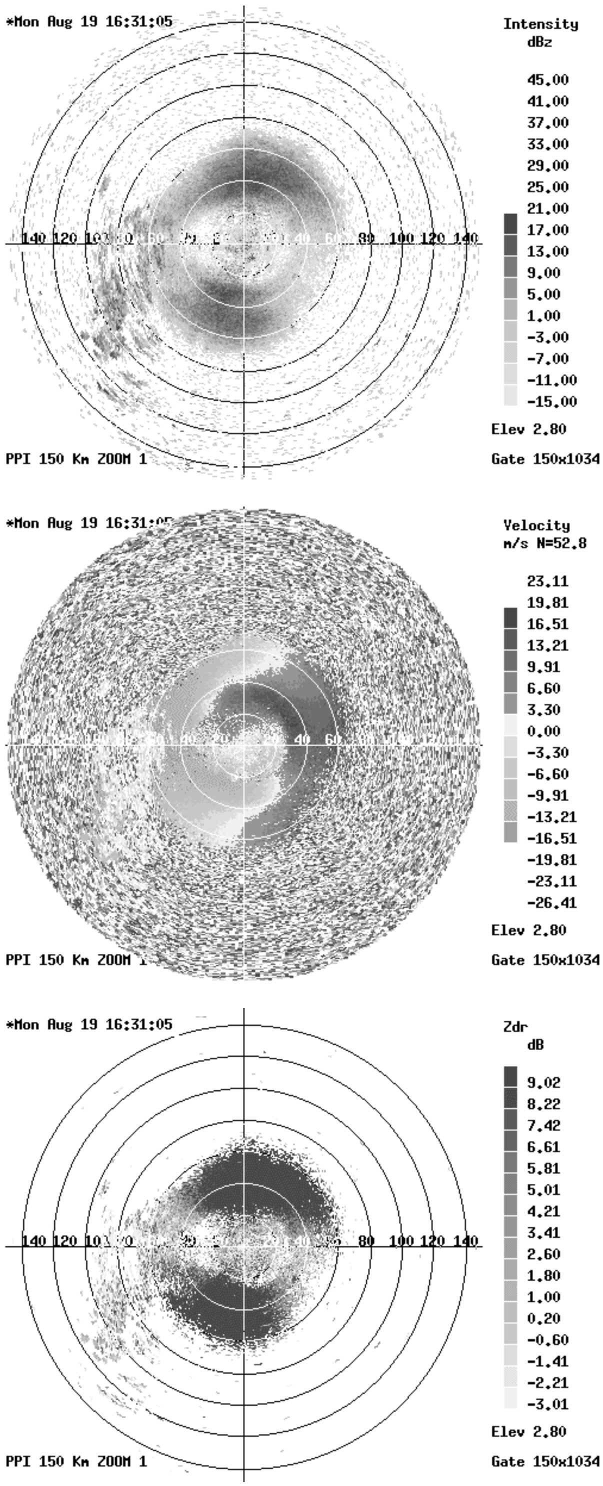

Figure 1. PPIs of Z_H (top), radial velocity (middle), and Z_{DR} (bottom), for elevation 2.80° at 1631 UTC on 19 August 2002.

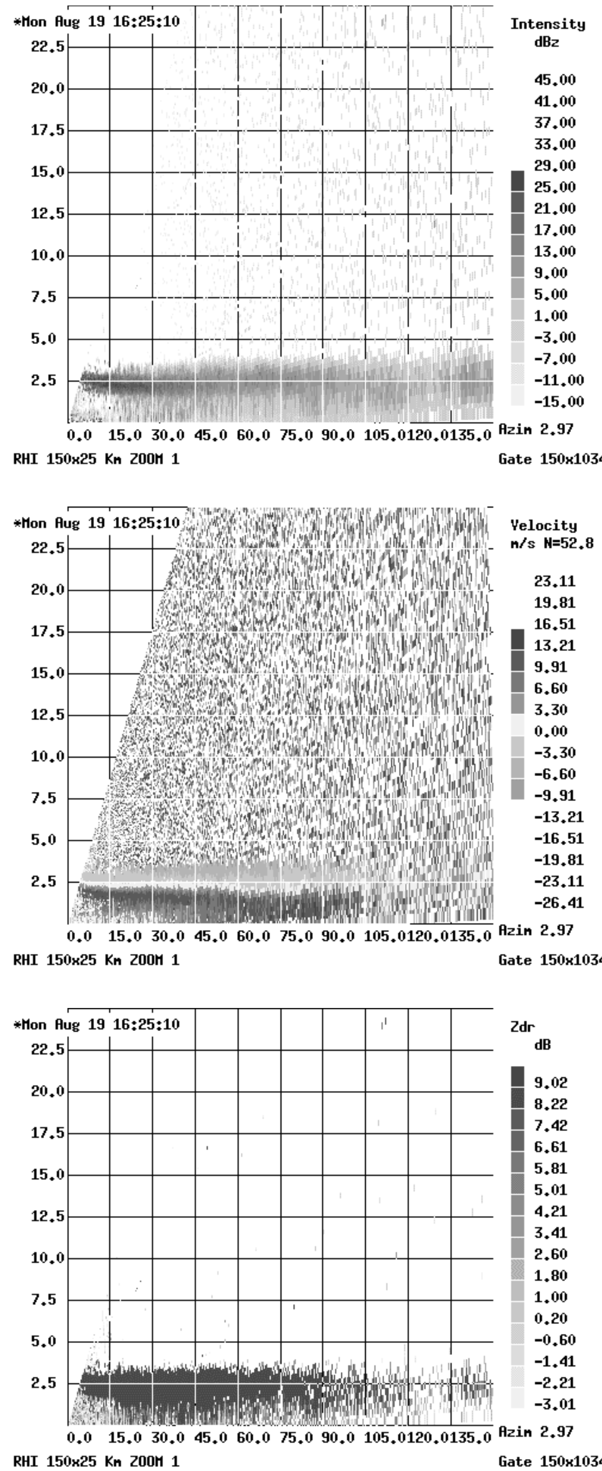

Figure 2. RHIs of Z_H (top), radial velocity (middle), and Z_{DR} (bottom), for azimuth 2.97° at 1625 UTC on 19 August 2002.

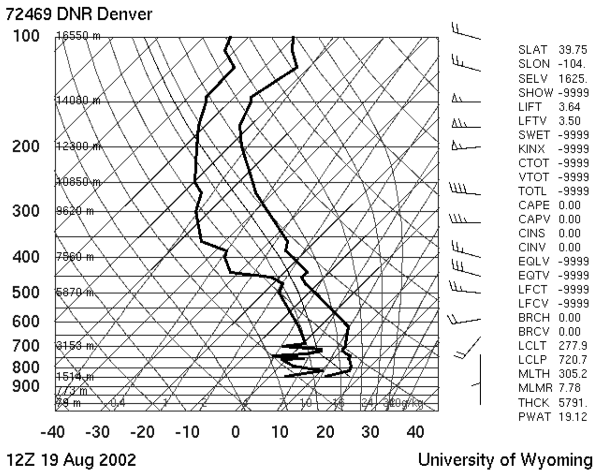

Figure 3. Skew-T/log-p plot for the 12 UTC sounding from Denver on 19 August 2002, obtained from the University of Wyoming database.

Figure 4. Two photographs looking roughly west from the CSU-CHILL radar. The top is from 9 October 2002 and shows the mountain view obscured by haze, while the bottom is from spring of 2003, with the normal mountain view. Photos courtesy of Pat Kennedy.

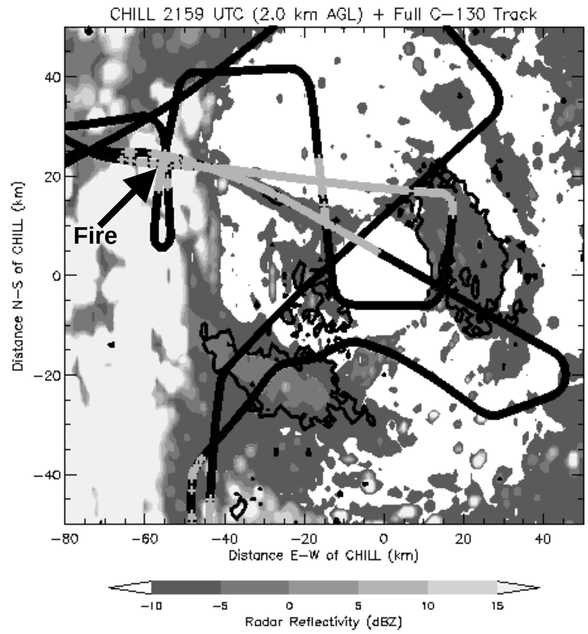

Figure 5. Horizontal cross-section of Z_H (relative to CSU-CHILL; shaded contours) along with Z_{DR} (> +4 dB outlined by black contour) at 2 km AGL from 2159 UTC on 17 October 2002. Superimposed is the NCAR C-130 flight track from this day (dark and light + signs). A dark track means out of plume, light track means in plume. Note the unfiltered ground clutter from the mountains ~50 km west of CSU-CHILL.

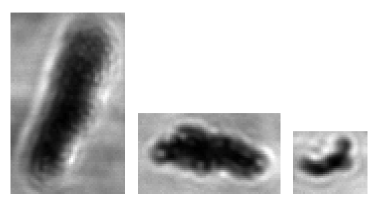

Figure 6. Large smoke particle images from the CPI instrument onboard the NCAR C-130. The largest particle (left) is approximately 200 µm along its major axis and images are to scale.

Fortuitously, *in situ* sampling of smoke from the 17 October fire occurred during an IDEAS2 project flight of the NCAR C-130 aircraft. The C-130 crew spotted a smoke plume from the Pingree Park fire and made several cross- and along-plume traverses during the time period 2027-2234 UTC, as CSU-CHILL made 360° surveillance scans. A horizontal cross-section of Z_H and Z_{DR} at 2 km AGL (relative to CSU-CHILL) from the 2159 UTC radar scan is shown with the complete aircraft flight track superimposed in Fig. 5. Data from the PMS probe onboard the C-130 was thresholded to determine whether the aircraft was in the plume or out of the plume. Interestingly, though the dumbbell-shaped echo pattern is located to the SW and NE of CSU-CHILL (winds were unidirectional with height and from the NW), the aircraft instruments did not indicate smoke particles in those areas. In fact, the plume as viewed by the aircraft was < 20 km wide and oriented in the low-reflectivity region to the NW. CSU-CHILL saw some echo in this region along the actual plume axis, but only –10 to –5 dBZ, and with lower Z_{DR} values than in the dumbbell echoes. Curious, too, was that the C-130 flew mostly above 3 km AGL, while CSU-CHILL saw little echo above this altitude. Evidently, the radar was observing larger particles falling out of the narrow plume to the NW while the C-130 flew in a region containing smaller (and thus less reflective) particles.

Some examples of the particles observed by the C-130 can be found in Fig. 6. The particles are indeed quasi-prolate in shape. However, they are very small (~200 μm and below), though they were found in concentrations (~10^{-3} cm^{-3}) that made them able to account for Z_H of approximately –10 dBZ, as observed.

Because the fire source was ~60 km WNW of CSU-CHILL, it is not likely that the smoke could have spread to the large dumbbell regions to the NE and SW of CSU-CHILL. A similar argument could be made for 9 October, which had dumbbell echoes oriented in roughly the same direction (similar wind direction). This argument is based on simple plume dispersion models, which predict widths < 20 km at distances < 100 km from the point source, under likely stability scenarios for these days (Seinfeld 1986, chapter 14).

Also factoring against the smoke hypothesis is the requirement for a preferred particle orientation to explain the observations. Though prolate-shaped particles like ice crystals are known to fall with their major axis aligned horizontally, parallel to the ground (Pruppacher and Klett 1997, chapter 10), it is unclear how such small particles would be additionally oriented along the direction of the mean wind, since they would tend to be advected with the wind and thus experience no net torque to orient them in a preferred direction, except for being subject to small-scale turbulence that would, if anything, orient them randomly.

3.2 *Insect Hypothesis*

The insect hypothesis is more attractive, since dumbbell-shaped radar echoes have been observed before with migrating insects (e.g., Mueller and Larkin 1985). The main problem is that previous insect observations with CSU-CHILL in NE Colorado generally show them near the ground, as components of fine lines and other clear-air features, not aloft in a narrow vertical layer. However, soundings from all three days (e.g., Fig. 3 for 19 August 2002) indicate that the altitudes containing the radar targets were primarily at temperatures above 0 °C. Thus, it would be possible for insects to remain in this altitude range without experiencing freezing. In addition, insects have been observed up to the freezing level altitude in other parts of the U. S. (D. Atlas, personal communication), so the idea of insects aloft is realistic.

The insects would not rise to such an altitude voluntarily, since they would be away from food sources near the ground, and out of their preferred temperature range. They may 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). In addition, there have been vestiges of the dumbbell pattern, though not as intense as the aforementioned three days, observed on a few other non-fire days during the fall 2002 and spring 2003, lending additional credence to the insect hypothesis over that of smoke.

4. CONCLUSIONS

Combined polarimetric and Doppler data from the CSU-CHILL radar was used in concert with atmospheric sounding, satellite, and *in situ* aircraft data to infer the nature of widespread dumbbell-shaped echoes situated near the top of the boundary layer on three separate days in the summer and fall of 2002. The data are consistent with quasi-prolate particles aligned horizontally along the mean wind axis. The most plausible explanation for the nature of the targets are that insects were buoyed aloft by thermals, possibly due to nearby fires, and proceeded to align themselves with the mean wind.

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