P2.4

FINE-SCALE OUTFLOW STRUCTURE OF THE 10 JULY 2001 GREELEY, CO CONVECTIVE WIND EVENT

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1. INTRODUCTION

On the evening of 10 July 2001, an intense macroburst and associated outflow moved through portions of southern Weld County, Colorado causing considerable damage. The area near Greeley experienced the most damage with power outages to about 10,000 homes and businesses, and approximately 20-30 % of the area's crops damaged. Total property and crop losses were estimated at 3 million dollars (*Storm Data*, NCDC). Minor flooding followed the wind damage. Fortunately, the outflow core made a direct passage over the CHILL radar site, allowing for the collection of high-resolution data as the outflow propagated both inbound and outbound within 15 km of the radar. Analysis of the radar data revealed winds of 44 m/s just 50 m AGL as the outflow passed over Greeley.

The study of thunderstorm outflow dynamics and morphology is ultimately important for understanding regions of potentially damaging surface winds and dangerous wind shears of importance to the aviation community. A better understanding of boundary instabilities will also likely improve our understanding of moist convective forcing (Lee et al., 2000). A companion numerical modeling paper (P6.7) is included in this volume that investigates fine-scale outflow instabilities in an idealized environment. A concerted focus over the next several years will be on the investigation of the fine-scale structures of boundaries with projects like IHOP and studies using fixed-base research radars like the Colorado State University (CSU) CHILL (positioned in the usually boundary-rich region of northeast Colorado).

The severe outflow event featured here allowed for a rare opportunity to obtain high-resolution radar data of the three-dimensional structure of a strong outflow. Of particular interest is the documentation of lobe and cleft instability (LCI, Simpson 1972) located in the gravitationally unstable region near the outflow nose where less-dense air is overrun by the outflow. We hypothesize that LCI may be associated with large horizontal and vertical wind shears (of concern to aviation) and may induce localized wind maxima associated with initial wind damage in severe outflows. The relationship between LCI and horizontal shearing instability (manifest in gustnadoes) is under current investigation by the authors. LCI has received very little attention in the atmospheric sciences community likely due to the difficulty in studying phenomenon on this scale (~200 - 400 m). Kelvin Helmholtz instability (KHI) was also present atop this outflow boundary and is shown in the radar analysis of section 3.

Unlike the wealth of observational and modeling documentation of KHI associated with outflows, there are very few references to observed lobe and cleft instability. While most people with an interest in meteorology have seen pictures or video of dust-filled outflows (often called *haboobs,* see Simpson 1997) with highly perturbed, three-dimensional leading edge structure, most probably did not realize they were looking at a specific gravitational instability. The atmospheric observational documentation of LCI is quite meager. Mueller and Carbone's (1987) dual-Doppler study of a Colorado outflow revealed a possible pattern of superimposed LCI at the outflow leading edge. Intrieri et al. (1990) employed Doppler lidar to identify lobe and cleft structure on the leading edge of a Colorado outflow boundary. Ohno and Suzuki (1993) identified small high wind cores of a few hundred meters in scale length along the leading edge of the sea breeze that were suggestive of LCI.

2. DATA COLLECTION

Data was collected on this event during a project the authors had with the CSU National Radar CHILL Facility. The project's objectives included obtaining data on misocyclone circulations along atmospheric boundaries, and gathering high-resolution radar data sets of the near-leading edge region of strong and moderate thunderstorm outflow boundaries. Data was collected with the CHILL radar and some instrumentation at the University of Northern Colorado. As luck would have it, a mesonet station co-located with CHILL had received a prior lightning strike and was disabled, and a power outage truncated the ASOS transmission. A discussion of CHILL radar specifications may be found in Brunkow et al. (2000). With a range gate size of 49 m (in the scanning mode used for this study) and a 1.1° beam width, it was anticipated that LCI would start to be resolved at about 10-12 km with ample resolution inside of 5 km. To obtain the three-dimensional structure near the outflow leading edge, an alternating pattern of RHI and PPI scans were utilized. In general for RHI scans, 3 azimuth angles were collected, and for PPI scans, 4 elevation angles were used. Given the larger nature of the KHI on this day, they could be observed out to approximately 15 km.

3. OBSERVATIONS AND ANALYSIS

The northeast Colorado thunderstorms of this evening occurred on the western side of a large upper-

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level ridge that was a dominant factor in the suppression of deep convection over much of the central and western High Plains in the weeks preceding this event. With the ridge axis to the east of Colorado, periodic weak short waves propagating northward were key factors in the deep convection on this day and several days that followed. Upper-level flow was southerly and weak with just 30 kt winds at 250 mb. Modifying the Denver 00Z sounding for Greeley's surface temperature (27 ^{o}C) and dew point (16 ^{o}C) in the environment just preceding the storm yielded a surface-based LI of -7 ^{o}C and CAPE of 2200 J kg^{-1}. The dew point depression of 11 ^{o}C, although not unusually large, certainly contributed to outflow production from the storms of this evening.

Evidence of the macroburst was first observed approximately 35 km southwest of CHILL at 0142 Z (11 July UTC). As it matured, a CHILL radial velocity PPI collected at 0207 Z and shown in Fig. 1 displayed a striking semi-circular macroburst leading edge 11 km southwest of CHILL. A close examination of the leading edge reveals a pattern of perturbations that could be poorly resolved LCI. The outflow's propagation speed was 13.7 m s^{-1} as it approached the radar with peak internal radial velocity at this elevation angle just exceeding 32 m s^{-1}.

As the outflow leading edge neared the radar site, the LCI structures became more apparent as may be seen in the boundary-relative radial velocity PPI images at 0215 Z in Fig. 2. In this figure, 2 elevation angles give some vertical contrast of the leading edge structure. Although the 1.3^{o} image is riddled with ground clutter, some valuable information can still be garnered from it where the return has some coherency (east of a 225^{o} radial). With much of the leading edge near 5 km from the radar, small structures are now better resolved. Apparent at both elevation scans are small-scale patterns of lobes and clefts that delineate the detailed leading edge. To see if the length scale of the lobes matched that predicted by prior laboratory work, we identified 41 coherent lobes along the outflow leading edge on the 2.5^{o} scan. The average lobe was 268 m. Simpson (1972, 1997) found that for Reynolds Numbers (Re) greater than 4000 (he tested Re from about 300 to approximately 11000) that the ratio of average lobe size to outflow head height was relatively constant at about 1/4. If we extend that ratio to the even higher Re of atmospheric flows, we would expect that for the head height of this outflow (1200 m), that the average lobe length would be 300 m.

Another striking facet of the leading edge structure involves a much larger scale lobe structure. These "superlobes" may be seen at both elevation angles, but are easiest to pick out at 2.5^{o}. White arrows have been inserted in the 1.3^{o} and 2.5^{o} scans to indicate giant cleft structure between these superlobes. Superposed on these superlobes is the anticipated pattern of LCI. The giant clefts appear to leave behind kinematic channels in the flow but only in the lowest several hundred

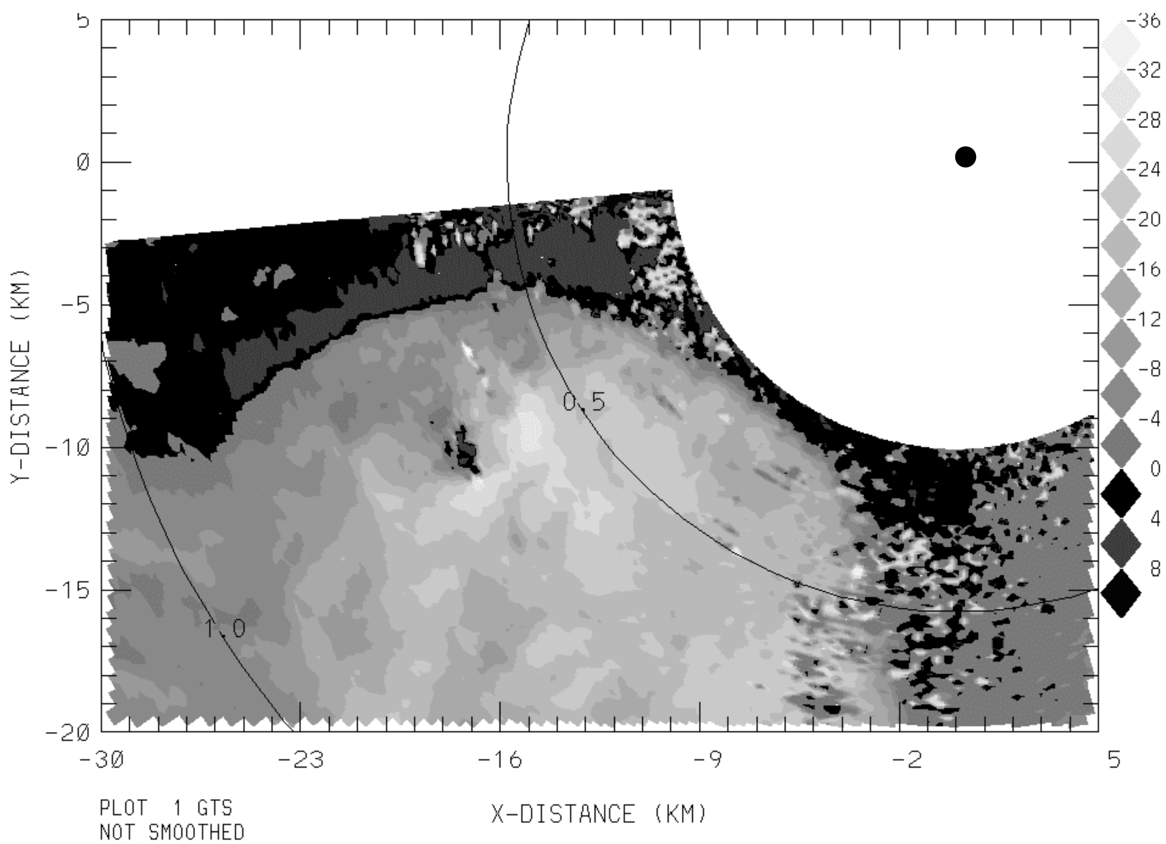

Fig. 1. PPI of radial velocity at 0207 Z. Elevation angle is 1.8 ^{o} and the rings indicate the beam height above the surface in kilometers. The velocity has units of m s^{-1}. The black dot indicates the CHILL site.

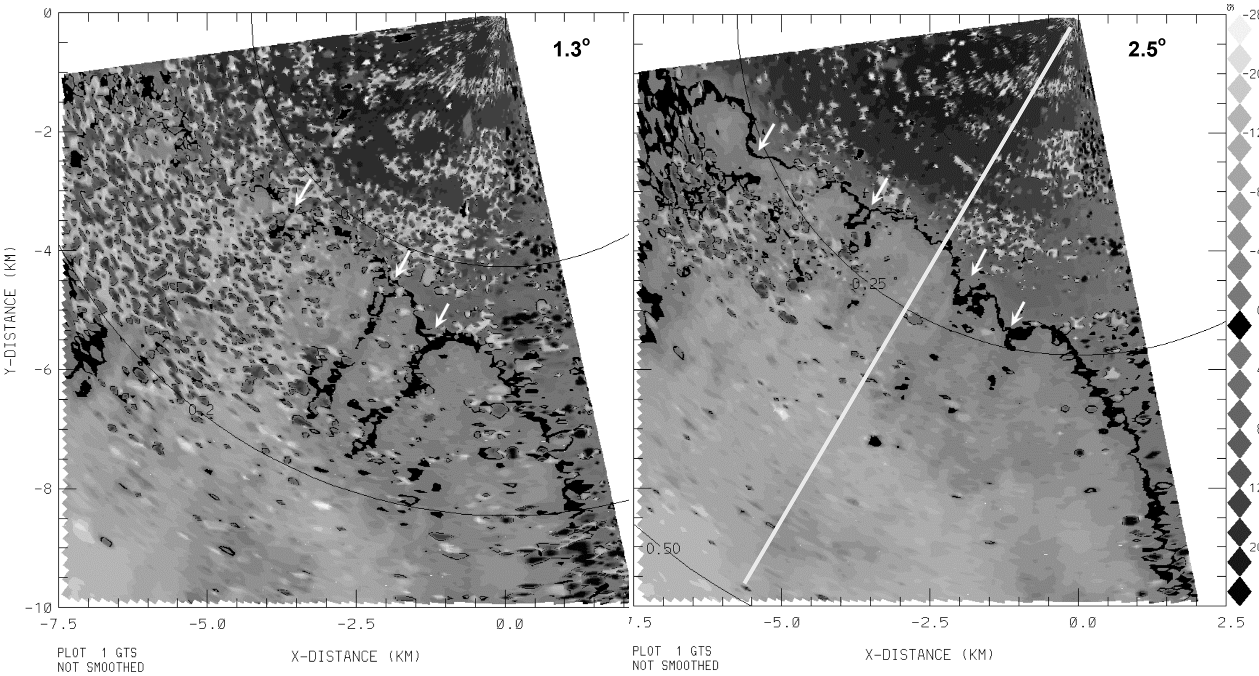

Fig. 2. PPI plots of the boundary-relative radial velocity at elevation angles of 1.3° and 2.5°. The time was 0215 Z. The white arrows are explained in the text. The gray line represents the azimuth angle for the RHI scans presented in Fig. 3

meters as evidenced by only a very weak signal of these channels in the 3.7° scan (not shown). These channels represent significant internal shear regions while the leading edge clefts are likely regions of updraft jets based on idealized modeling of LCI (see companion paper P6.7). How persistent and prevelent these superlobes are remains an area for future analysis and more data sets. The superlobes are faintly present at the time of Fig. 1 (although the grayscaling makes this difficult to see) and they are still present in subsequent scans but appear far more damped. This leads to the question of why they are present. Possibly the superlobes are there due to inhomogeneities in the storms outflow forcing, such as imbedded microbursts within the leading part of the macroburst. Perhaps the superlobes are present because of major changes in surface friction as the outflow moved from short grass prairie and short crop land to the greater Greeley area. Roughness lengths would have varied from a few centimeters in the agricultural regions surrounding Greeley to 0.5 - 1.0 m over Greeley (Landsberg 1981). Might the rapid increase in drag coefficient have had an impact on the LCI structure such that a new, larger scale LCI mode was realized (in addition to the 268 m mode)? Additional modeling and case data may provide an answer to this question.

The storm and outflow vertical structure is shown with RHI imagery in Fig. 3. The outflow is approaching the CHILL site during these scans. A perspective of the outflow in relation to the anvil overhang (and associated precipitation fallout) and the main precipitation core is readily apparent in the reflectivity plot. At this time, the outflow leading edge extends about 8 km in front of the edge of the precipitation core. The raised reflectivity areas atop the outflow correspond to the KHI pattern seen in the middle panel of Fig. 3. Outflow-relative wind vectors were constructed using the radial velocity and derived vertical velocity from the integration of the continuity equation. Fortunately, the flow along this azimuth was largely parallel to the radial, lending somewhat more confidence in the vertical velocity calculation, although there were still pockets of noise. A series of KHI may be seen atop the outflow and are propagating rearward with respect to the leading edge. The third panel shows the outflow leading edge only 3.6 km from CHILL and provides an excellent depiction of the elevated head. Strong vertical shear zones rearward of the head correspond to KHI waves. The inset shows what we believe is the outflow nose (see left arrow), elevated approximately 100 m above the surface and extending about 150 m in front of the surface boundary. Both of these nose characteristics compare favorably to the tower studies of Goff (1976) and the Simpson's (1997) analysis of laboratory and atmospheric studies of density current nose height data. Given some uncertainty about the exact elevation of the ground at the nose location, these numbers should be considered as approximate until a more detailed topographic analysis is done. The inset also shows a broader shallow structure (right arrow) of several hundred meters depth we believe is a lobe. This is consistent with the RHI radial passing through a lobe position shown in Fig. 2; however, we can not be sure of the exact lobe configuration at the time of the RHI.

4. CONCLUSIONS

A fortunate passage of a severe outflow over the CHILL radar on 10 July 2001 has allowed for the collection and subsequent analysis of radar data of

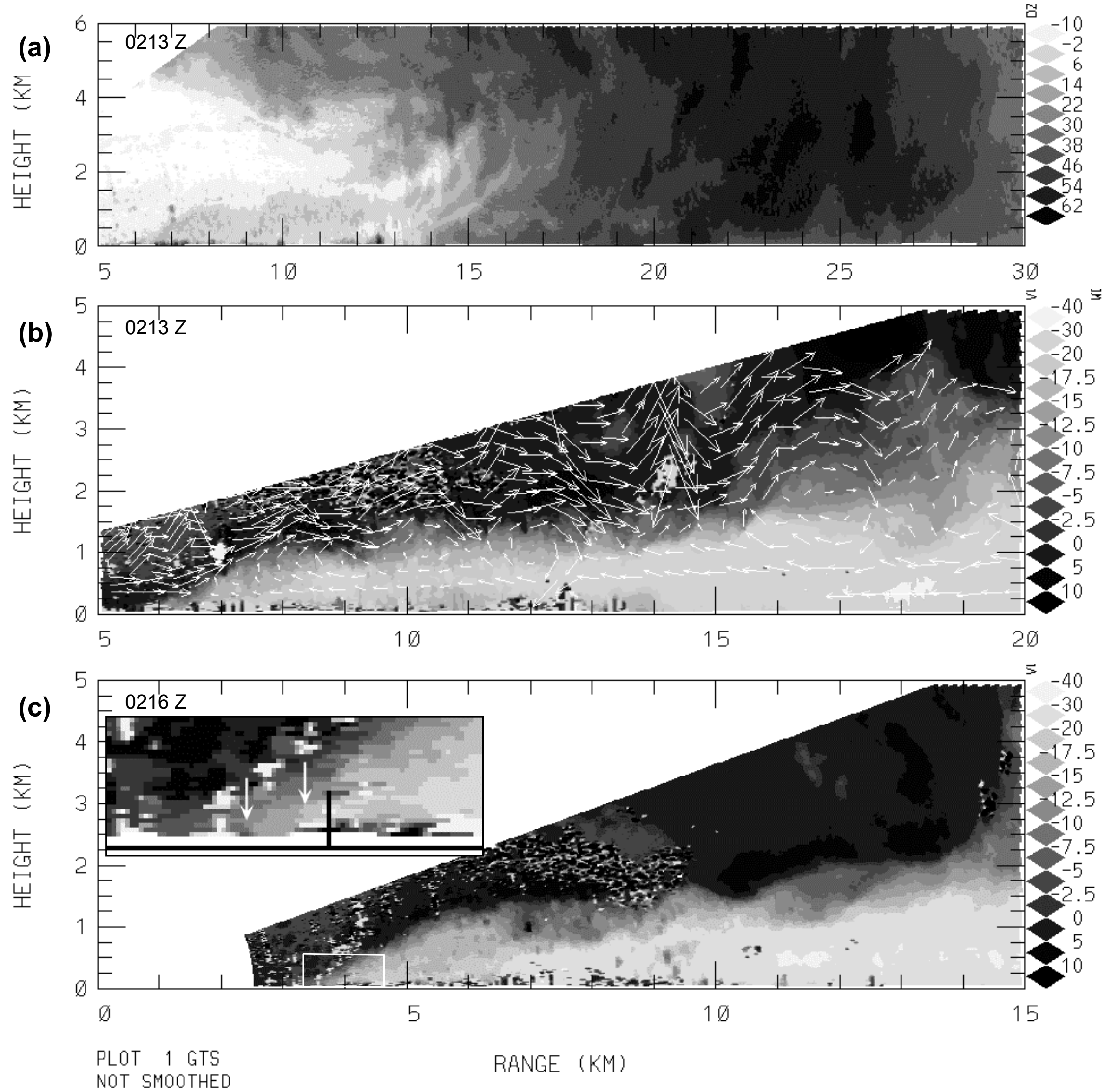

Fig. 3. RHI scans at an azimuth angle of 210^{o} for a) reflectivity at 0213 Z, b) radial velocity with overlaid outflow boundary-relative vector winds at 0213 Z and c) radial velocity at 0216 Z. The inset in **c** is the area bounded by the white rectangle and is discussed in the text.

sufficient resolution to depict rarely-documented fine-scale features along and near the leading edge of the outflow. Further analysis of this data set is underway to identify the relationship between local speed and shear maxima and LCI and KHI positions.

5. ACKNOWLEDGEMENTS

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