Rear-Flank Outflow Dynamics and Thermodynamics in the 10 June 2010 Last Chance, Colorado, Supercell

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ABSTRACT

On 10 June 2010, the second Verification of the Origins of Tornadoes Experiment (VORTEX2) armada observed a supercell thunderstorm near Last Chance, Colorado. Tempest unmanned aircraft system (UAS) data collected in the rear-flank outflow revealed what appeared to be an elevated outflow head, turbulent wake, and a cold rear-flank internal surge (RFIS). Surface thermodynamic and kinematic data collected by the StickNet and mobile mesonet indicated that the outflow wake may have extended to or very near the surface, perhaps modifying or outright replacing the leading edge of the outflow at times. Single-Doppler data collected by the NOAA X-Pol Mobile Polarimetric Doppler Radar (NOXP) were supportive of the possibility of a downdraft in the outflow wake associated with low-level divergence. A conceptual model of the hypothesized rear-flank outflow structure in the nontornadic phase of the Last Chance supercell is presented. The observed turbulent wake is consistent with mixing associated with the release of Kelvin–Helmholtz instability rearward of a density current head. Observations also support the hypothesis that the RFIS would not have existed without the turbulent wake.

1. Introduction
   a. Background

   The rear-flank downdraft (RFD) plays a critical role in the long-standing conceptual model of supercell tornadogenesis [the reader is referred to the review of Markowski et al. (2002) and references therein]. In situ observations of near-surface thermodynamic fields indicate that RFDs characterized by higher thermal buoyancy are more likely to support tornadogenesis possibly as a result of a higher potential for air in the RFD to accelerate upward and increase its vertical vorticity via stretching (Markowski et al. 2002; Grzych et al. 2007; Hirth et al. 2008; Lee et al. 2012). However, it is also likely that the RFD realigns and distributes vorticity that is generated baroclinically within the RFD (Davies-Jones and Brooks 1993; Straka et al. 2007), suggesting that tornadogenesis may also be less likely to occur in the absence of a horizontal buoyancy gradient (i.e., having outflow that possesses too little of a buoyancy deficit for baroclinic vorticity generation). It follows that a deficit in the thermal buoyancy of RFDs may be a favorable condition for the formation of horizontal vorticity, which may be converted into vertical vorticity via tilting. Therefore, there may exist a range in the thermal buoyancy within RFDs (relative to the surrounding air mass) that is most supportive of tornadogenesis and tornado maintenance (Markowski et al. 2008).

   Recent in situ observations (e.g., Marquis et al. 2008; Mashiko et al. 2009, Lee et al. 2012; Kosiba et al. 2013; Skinner et al. 2014) have identified momentum surges behind the primary rear-flank gust front (RFGF), hereafter referred to as rear-flank internal surges (RFISs), as being instrumental in leading to surface convergence and the vertical stretching of vertical vorticity and, subsequently, tornadogenesis. The potential importance of RFIS formation with regard to tornadogenesis underscores the importance of diagnosing the kinematic and thermodynamic processes that lead to their occurrence. While these studies identified rear-flank internal surges by increases in momentum (hence,
the use of the term "surge"), a momentum increase was not documented in the 10 June case. Rather, a wind shift (characterized by confluent flow) within the larger-scale rear-flank outflow (RFO) was observed. Because the presence of convergence along this wind shift was inferred from Tempest unmanned aircraft system (UAS) altitude data (as will be discussed later), and because this inferred region of convergence existed behind the primary RFGF, for the purpose of this study, the momentum increase requirement for an RFIS is being relaxed since convergence along a wind shift boundary may be important in a similar manner to convergence along other RFIS boundaries.

In this article, results are presented from an examination of the RFO and RFIS during the posttornadic phase of the 10 June 2010 “Last Chance supercell” during the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2; Wurman et al. 2012). This dataset is composed of observations of the RFGF, RFO, and RFIS collected by the NOAA X-Pol Mobile Polarimetric Doppler Radar (NOXP), the Shared Mobile Atmospheric Research and Teaching Doppler radar [SMART-R 2 (SR2)] (Biggerstaff et al. 2005), StickNet (Weiss and Schroeder 2008), mobile mesonet surface observing platforms, and UAS (Elston et al. 2011). This dataset is unique in large measure because surface observations of these features were accompanied by UAS observations. This juxtaposition provided a unique opportunity to study the vertical thermodynamic structure of a rear-flank outflow.

b. Overview of the Last Chance case

Two supercell thunderstorms formed in an upslope flow regime in northeastern Colorado late in the afternoon on 10 June 2010. One supercell initiated at about 2230 UTC and eventually underwent a merger and weakened (Klees et al. 2016). A second supercell, hereafter referred to as the “Last Chance supercell,” because of its proximity to Last Chance, Colorado, also initiated at around 2230 UTC and produced two tornadoes between about 0108 and 0127 UTC (Klees et al. 2016). After this tornadic phase, the RFGF moved well ahead of the midlevel mesocyclone and tornado production abated. The structure and evolution of the RFO during this nontornadic phase, particularly from 0128 to 0210 UTC, form the focus of this study. The reader is referred to the work of Klees et al. (2016) for analysis and discussion of the interaction between the northern and Last Chance supercells as well as an in-depth analysis of mesocyclone evolution during a nontornadic phase of the Last Chance supercell.

During its posttornadic phase, the Last Chance supercell was embedded in an environment (Fig. 1) characterized by moderately large mixed-layer CAPE
(MLCAPE) in the range of $2400–3627 \, \text{J kg}^{-1}$, an inversion between 700 and 800 hPa, steep midlevel lapse rates (nearly dry-adiabatic), and moderate low-level shear ($0–3$-km storm relative helicity values ranged from 145 to $163 \, \text{m}^2 \, \text{s}^{-2}$) (UCAR/NCAR 2010). Since the three soundings used failed to reach the respective equilibrium levels, MLCAPE values were directly quoted from Klees et al. (2016), in which data from a 2342 UTC sounding were used to estimate the upper-level environment thermodynamics, which the 0137–0140 UTC soundings failed to sample. Figure 2 shows the location of the three soundings launched from 0137 to 0140 UTC and used to represent the environment relative to the supercells at 0137 UTC.

Between 0148 and 0204 UTC, the RFGF (denoted by the dashed white line in Fig. 3) moved to the east toward NOXP. As the RFO expanded to the east, a region of outbound radial velocity became clearly visible to the rear of the RFGF (though these velocity data were in a region of very weak signal), followed by a second area of inbound radial velocity farther to the west (Fig. 3). While not shown in Fig. 3, these flow features appeared at intermediate (2 min) radar scans, indicating that they were persistent. Because of the temporal continuity of the radial velocity structure described above, these features were analyzed despite the weak signal within which some were embedded. The secondary area of inbound radial velocity is referred to as the RFIS [the attendant RFIS boundary (RFISB) is denoted by the broken dark blue curve]; this is the RFIS that the UAS, scout mesonet, and StickNet sampled. Meanwhile, the hook echo moved eastward as well, and took on a flared-out shape (Bluestein et al. 2014).

**2. Methodology**

a. Radar data

NOXP (Burgess 2011), an X-band dual-polarimetric Doppler radar, collected shallow volume scans with seven elevation tilts ranging from $1^\circ$ to $7^\circ$ (Table 1). NOXP data were manually quality controlled using Solo3 to align ground clutter with nearby surface clutter targets, subsequently remove ground clutter, remove multiple trip echoes, and dealias the radial velocity. Data were not corrected for advection (because of the short temporal span of sweeps composing an NOXP volume). Additionally, radial position errors existed in some higher tilts in the NOXP dataset. These radial offsets were related to blocks of missing radial data in regions outside of the region of interest (rear-flank outflow, hook echo). These radial offsets were manually corrected by aligning storm-scale features (such as the hook echo) to positions in adjacent elevation angles.

b. Coordinate system methodology

Previous studies have examined the characteristics of RFOs in supercells by placing surface in situ observations (both from moving and stationary platforms) into a storm-relative reference frame (e.g., Markowski et al. 2002; Lee et al. 2004; Grzych et al. 2007; Lee et al. 2012; Klees et al. 2016). Thermodynamic and kinematic analysis of the Last Chance supercell could have similarly been performed within a storm-relative framework [as was described by Klees et al. (2016)]; however, the focus of this work is solely on the rear-flank air masses and attendant boundaries and the RFGF did not maintain a constant position relative to the midlevel mesocyclone, thus, placing data in coordinates with respect to the midlevel mesocyclone could not be assumed to produce an analysis that retains information about RFGF-relative positions. Therefore, in situ data were placed within a *boundary-relative* reference frame.

The initial steps taken to place data collected by the Tempest UAS, StickNet (Weiss 2010a,b), mobile mesonet (Richardson and Markowski 2010), and scout mesonet into boundary-relative coordinates involved subjectively analyzing the position of the RFGF with radial velocity and reflectivity observations collected by the Denver, Colorado (KFTG), Weather Surveillance Radar-1988 Doppler (WSR-88D), SR2 (Biggerstaff and Wicker 2012), and NOXP. The reader is referred to Table 2 for a list of boundary position analysis times and other specifications. Sets of latitude–longitude coordinates were recorded for each RFGF position by annotating boundaries in the Integrated Data Viewer (Unidata 2015) based on the positions of reflectivity

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1 The soundings were plotted and indices calculated using the SHARPPy package (Halbert et al. 2015).
FIG. 3. NOXP (left) uncorrected reflectivity (dBZ) and (right) radial velocity (m s$^{-1}$). White broken curves indicate the positions of the RFGF, blue broken curves indicate the positions of the RFISB, and broken red curves indicate the positions of the leading edge of outflow wake. Eight-minute intervals are shown, starting at 0148 UTC and ending at 0204 UTC. All except 0204 UTC are 2.0°-elevation plan position indicators (PPIs); the 0204 UTC scan was taken at 3° elevation.
finelines and inbound–outbound radial velocities at 0.8°–3.0° tilts. As boundaries were drawn farther south of the storm, the positions of the southern ends of the boundaries became more approximate as a result of weaker signal returns. While this was done to include some of the southernmost StickNet observing stations in the analysis, the boundary-relative positions at the southern edge of the domain should be considered more approximate than those farther north.

Once boundary positions at fixed analysis times were collected, intermediate RFGF positions were calculated to create a set of RFGF positions spanning the analysis time frame. First, the predetermined boundary positions were linearly interpolated to splines on a 0.00018 spaced latitude grid, such that along each respective latitude parallel, there existed a set of longitude values that defined east–west positions of the RFGF at different times. Between the fixed analysis times, intermediate longitude values were computed along latitude parallels via linear extrapolation at a 1-Hz frequency, which resulted in a set of latitude–longitude coordinates approximating the RFGF position for every second during the analysis period. Thus, the interpolation along separate latitude parallels accounted for differential boundary motion in the west-to-east direction.

The positions of instruments relative to the RFGF were then calculated. Data from each instrument were linearly interpolated to a 1-Hz frequency. Each instrument’s (stationary and moving) distance from the RFGF was calculated using the haversine function, where for every second that data existed, the minimum distance to any point along the RFGF was calculated. If the observation was collected west of the gust front, the distance was recorded as a negative number, while observations east of the gust front were recorded as positive distances. Data that were collected north or south of the predefined latitude grid were excluded from the analysis.

c. StickNet methods

StickNet platforms (Weiss and Schroeder 2008) recorded pressure, temperature, relative humidity, and wind speed and direction. All StickNet platforms recorded these data at either 10, 5, or 1 Hz. Data not recorded at 1 Hz were subsampled for boundary-relative coordinate system processing to a 1-Hz frequency. StickNet data used for this analysis are from a 12-unit south–north array deployed along Colorado Highway 71 (Fig. 4). Automated quality controls were also applied to StickNet data in order to remove bad or questionable thermodynamic data and wind data (Weiss and Schroeder 2008). Missing data points (of which there were a few from several of the StickNet pods) were excluded from the StickNet potential temperature traces.

Pressure data from the southernmost probe were subjectively determined to be too high as well, so thermodynamic variables from this probe were excluded from the analysis. Upon inspection of mass test data, StickNet pod temperatures that were plotted should be roughly within 0.7 K of each other. One of the pods, 0104A, exhibited a high temperature bias of ~2 K in the mass test; however, upon visual inspection of the potential temperature data shown later (Fig. 10), these data do not appear to have any bias compared to StickNet pods to the north or south within the RFO or in the pre-RFGF environment. No calibration was attempted between the different types of instruments (e.g., UAS, StickNet, mobile mesonet) because of time constant differences. Before being plotted on a RFGF-relative plot, wind data were converted to their u and v components and then smoothed with a Gaussian filter. No calibration was attempted for surface wind data collected by StickNet, Pennsylvania State University (PSU) mobile mesonets, and scout mesonet; thus, the exact degree of accuracy of the wind data is unknown. However, the continuity in results between the different instrument suites lends confidence to drawing conclusions from the results.

d. Tempest UAS methods

The Tempest UAS (Fig. 5) collected pressure, temperature, and relative humidity data using a Vaisala
RS-92 sonde, with an accuracy of ±0.5 K for temperature, ±1 hPa for pressure, and ±5% for relative humidity data. The “reproducibilities” for these measurements were 0.2 K, 0.5 hPa, and 0.2%, respectively, and these reproducibility numbers were used to calculate the expected spread in the derived water vapor mixing ratio and potential temperature via a Monte Carlo sampling technique, which resulted in a 0.37–0.49 g kg\(^{-1}\) spread for the water vapor mixing ratio and a 0.22-K spread for potential temperature. Three-dimensional wind data were derived through a proprietary algorithm within the Cloudcap Technologies Piccolo SL autopilot but quality control revealed that these data did not have research grade accuracy. Altitude data were also recorded from GPS altitude measurements.

3. Results

The Tempest UAS sampled the environment to the southeast of the Last Chance supercell and in the supercell’s RFO. Data were collected from 0128 to 0204 UTC, mainly on a north–south trajectory along Colorado Highway 71 as the primary RFGF and a RFIS translated from west to east across Colorado Highway 71 (Fig. 4) to the south of the flared-out hook echo. As discussed previously, the UAS sampled three distinct features within the RFO. First, the primary RFGF can be seen as a gradual decrease in equivalent potential temperature \(\theta_e\) at approximately 0141 UTC (Fig. 6). The equivalent potential temperature then gradually decreased for the following 5 min, which would be expected as the UAS penetrated deeper into the RFO. An increase in \(\theta_e\) followed from 0147 to 0153 UTC. Equivalent potential temperature values during this period reached or exceeded those seen prior to the passage of the RFGF. A rapid decrease in \(\theta_e\) occurred from about 0153 to 0200 UTC, signifying the presence of a cold RFIS (Fig. 6). An increase in equivalent potential temperature to values near those in the air mass

Fig. 4. Locations of instruments. Radar image is NOXP 2.0° tilt at 0156 UTC, where the solid blue line represents positions of PSU mobile mesonet probes from 0150 to 0200 UTC, the solid green line represents all scout mesonet positions, the crimson line represents all UAS positions, the magenta square represents the location of the scout mesonet at 0156 UTC, the yellow airplane represents the position of the UAS at 0156 UTC, and the orange stars represent StickNet locations. NOXP is the red-outlined white hexagon near the right-center part of the figure.

Fig. 5. Tempest UAS on 10 Jun 2010.
immediately in front of the secondary outflow surge then occurred as the UAS traveled southward. Just before encountering the RFIS (around 0155 UTC), the UAS altitude rapidly increased by 42 m over a span of 25 s (Fig. 7). Since the aircraft autopilot was tasked to stay on an isobaric level corresponding to an AGL height of $375 \text{ m}$, this quick increase in altitude can be attributed to strong, small-scale upward air motion and/or a sudden increase in pressure (which the aircraft would react to by rising to return to its original isobaric surface). An increase in pressure was not observed (pressure decreased as the aircraft ascended); thus, the sudden increase in altitude is most likely a consequence of an updraft, which would be expected at the leading edge of an advancing cold RFIS. A smaller altitude increase occurred as the UAS exited the outflow surge at about 0200 UTC (about 5–6 min after the initial altitude increase), supporting the presence of an updraft tied to a persistent feature within the larger-scale outflow.

Equivalent potential temperatures derived from UAS observations suggest that a distinct air mass similar to the inflow air mass existed within the RFO. In the following analysis, the characteristics of this air mass aloft and at the surface will be examined within an RFGF-relative reference frame. To the west of the RFGF, the primary RFO manifests as a $\sim 1\text{ K}$ decrease in potential temperature (Fig. 8a). At about 4.5 km rearward of the RFGF, the potential temperature gradually increased back to values consistent with pre-RFGF air (Fig. 8a). The air mass to the west of 5 km was generally characterized by higher potential temperature. Additionally, several local maxima existed, one at about 6.5 km rearward of the RFGF, and two 8–9 km rearward of the RFGF. The first maximum in potential temperature was roughly collocated with the $\theta_e$ maximum within the wake (Figs. 8a,b). However, the second and third potential temperature maxima were located in a region where $\theta_e$ was relatively low (much closer to primary RFO values than to $\theta_e$ values within the wake). Rearward of the RFISB the potential temperature rapidly decreased to values below those found in the initial RFO.

Immediately to the west of the RFGF, in the primary RFO, $\theta_e$ decreased by 1–1.5 K (Fig. 8b). Equivalent potential temperature values then became more variable (though generally increased) from 4.5 to 5.5 km rearward of the RFGF. After this period of higher variability, $\theta_e$ increased by 2–3 K from 5.5 to 7 km rearward of the RFGF as the UAS progressed northward through the RFO (Fig. 8b). The $\theta_e$ values in this region met or exceeded $\theta_e$ values in the inflow environment to the east of the RFGF. Between 7 and 8 km rearward of the RFGF, $\theta_e$ again became more variable, and, aside from a few points more characteristic of $\theta_e$ in the wake, $\theta_e$ decreased back to values characteristic of the initial RFO. The region 8–11 km rearward of the RFGF was characterized by $\theta_e$ about 3 K lower than the initial RFO, signifying the presence of the cold RFIS. As the UAS progressed southward, it again encountered $\theta_e$ values more characteristic of the inflow air mass.

The same features in the RFO can be seen in other UAS-measured variables, with a few key differences. Water vapor mixing ratio data show an RFO that, in general, was slightly drier than the inflow air mass (Fig. 8c). In the localized regions of high potential temperature in the wake, water vapor mixing ratios reached local minima. The second peak in potential temperature (at about 8.5 km rearward of the RFGF) was also characterized by low water vapor mixing ratios (values at or below $13.4 \text{ g kg}^{-1}$), indicating that the warm air within the wake was also, in some areas, very dry. Low water vapor mixing ratio values were also present.
in the RFIS, compared both to the inflow environment and the initial outflow (Fig. 8c).

UAS thermodynamic data exhibited a spatial pattern consistent with an RFO that, above the surface, had been partitioned into an initial outflow head, a turbulent and much warmer wake region, and an RFIS. The initial outflow, in terms of both potential temperature and $u_e$, was cold with respect to the inflow environment, but warmer than the RFIS (Fig. 8). The large variability of potential temperature in the wake, in contrast to lower variability in the initial RFO, suggests the existence of turbulence, which would be expected behind the head of a density current where Kelvin–Helmholtz instability (KHI) would likely be released (Droegemeier and Wilhelmson 1987; Simpson 1997). Additionally, the higher potential temperature values in the wake, combined with a low water vapor mixing ratio, suggests that air within the wake came from outside the RFO.

UAS potential temperature and water vapor mixing ratio data are plotted on a Paluch diagram (Paluch 1979; see Fig. 9) along with smoothed potential temperature and water vapor mixing ratio data from the 0140 and 0137 UTC NCAR soundings (refer to Fig. 2 for the location of the soundings relative to the storm) in an effort to reveal possible source regions for the wake air mass within a conserved variable framework. Potential temperature and water vapor mixing ratio, for the purpose

Fig. 8. Tempest UAS (a) potential temperature, (b) equivalent potential temperature, and (c) water vapor mixing ratio in latitude vs distance spatial coordinates. The blue line represents the RFGF position, while UAS observations start in the bottom right and continue to the west.

Fig. 9. Scatterplot of water vapor mixing ratio (g kg$^{-1}$) and potential temperature (K) from the Tempest UAS along with curves denoting the 0140 and 0137 UTC NCAR soundings (0140 UTC sounding shown by the bottom-left continuous curve). Surface sounding values begin in the top left of each curve (color coded by height AGL), and end at the bottom right. Inflow observations were defined by RFGF-relative distances >0 m, initial RFO by $-4230 < \text{distance} < 0 \text{ m}$, wake by $-8570 < \text{distance} < -4230 \text{m}$, and RFIS by distance $<-8570 \text{ m}$, where wake observations were plotted from the first passage through the wake. All UAS observations are after launch.
of a conserved variable analysis, were treated as being conserved over the period of advection for parcels traveling from the inflow to the RFO. In order for this assumption to be valid for the scales being considered in this analysis, two assumptions were made. First, the total water mixing ratio was assumed to be conserved for any parcel as it advected into the RFO. Given that no precipitation was observed by radar along the RFGF to the south of the hook echo, any water vapor lost to cloud water was assumed to evaporate after parcels crossed over the RFGF, thus conserving the total water mixing ratio and allowing the water vapor mixing ratio to remain unchanged between its precondensation and postevaporation phases. Related to this assumption, diabatic processes that would warm or cool parcels traversing the RFGF were assumed to be fully reversible, thus conserving potential temperature between the precondensation and postevaporation phases. Assuming reversibility also depends on an assumption that most parcels sampled by the UAS in the wake region did not have trajectories that would have taken them through the precipitation farther to the north or around the mesocyclone. Rather, these parcels were assumed to have originated from somewhere in the environment and arrive in the RFO after being lifted over the RFGF. For the purpose of the conserved variable analysis, UAS data were subjectively partitioned into four categories: inflow (pre-RFGF environment), initial RFO (RFGF to wake), wake intrusion, and RFIS. The 0140 UTC sounding is included because it is positioned upstream relative to the east-northeasterly boundary layer flow (Fig. 2) and is characterized by thermodynamic conditions most closely aligned with UAS data collected in the pre-RFGF air mass. No assumptions were made about any diabatic processes that may have led to the initial cooling of the RFO (e.g., latent chilling from evaporating or melting hydrometeors). It is possible that the initial RFO may have been diabatically warmed as it advanced away from its source; however, the cooler/drier nature of the RFIS air (as compared to the initial RFO) could be explained by inhomogeneity in the precipitation field. Additionally, Klees et al. (2016) (studying the Last Chance supercell) and Beck and Weiss (2013) found an equivalent potential temperature trough deeper within the RFO; the cool/dry character of the RFIS is a consequence of the processes that lead to cooler/drier air appearing deeper within the RFO.

The wake air mass (denoted as red circles in Fig. 9) appears to fall along two mixing bands qualitatively determined from the available data. The first mixing band suggests that the wake air mass was a mixture of air from within the initial RFO observations (blue triangles in Fig. 9) and inflow air from altitudes between 500 and 1000 m, as evidenced by the placement of wake airmass observations (red circles) between the initial RFO and the 500–1000-m section of the 0140 UTC sounding line. Some wake observations have high potential temperature values that fall between the 0140 and 0137 UTC sounding lines, suggesting that some of the air in the wake may have been a mixture that included warmer air sampled by the 0137 UTC sounding (Fig. 9) and originating farther to the south (Fig. 2). Accounting for an error of ±0.22 K for potential temperature, the placement of these UAS observations between the soundings likely cannot be explained by instrument error. A second mixing band appears to lie between the initial RFO and a warmer and drier region at altitudes between 500 and 1000 m in the inflow. It follows from the placement of these two mixing bands that air from above the RFO and originating in the inflow air mass may have penetrated into the wake region. It is worth noting that, generally speaking, many of the wake parcels fall between the initial RFO region and the 500–1000-m inflow region, suggesting that air in the wake has a low-altitude origin. When a ±0.37–0.49 g kg\(^{-1}\) (due to internal variability) for water vapor mixing ratio is accounted for, some of the observations in the second mixing band are not clearly removed from those in the first, though many are near the outer edge of the spread that would be expected from measurement variability. Other differences in water vapor mixing ratios between subjectively categorized air masses, such as between the UAS initial RFO and the UAS RFIS, are more clearly established, even in the presence of possible instrument variability. Sounding observations will have similar error characteristics since they too rely on the RS-92 sonde. Considering the manufacturer-specified total uncertainty, the maximum uncertainty for water vapor mixing ratio for both the UAS and sounding data could range from 0.94 to as high as 1.24 g kg\(^{-1}\). Potential temperature uncertainty up to 0.54 K may also exist. The actual magnitude of these uncertainties is impossible to quantify with the available data. The interpretation presented here assumes uncertainties smaller than these maximum values.

While it has been established that relatively warmer air infiltrated the RFO above the surface, it does not necessarily follow that a wake intrusion would also be found at the surface. The scout vehicle for the UAS, which also traveled along a south–north trajectory along Colorado Highway 71, collected similar measurements to the UAS (for specifics on these measurements and subsequent data processing, see section 2b). Additionally, data from three PSU mobile mesonet probes, the scout vehicle for the UAS, and an array of StickNet platforms (Weiss and Schroeder 2008; Fig. 4), collected in situ surface thermodynamic data. Given the spatiotemporal proximity of
the UAS thermodynamic measurements to surface-based measurements, these datasets are compared to examine the vertical continuity (or lack thereof) of the features inferred from UAS data.

The surface-observing platforms encountered a similar pre-RFGF environment to that measured by the UAS. Air at the surface was generally warm and moist, with a maximum in potential temperature occurring near 5 km in advance of the RFGF (Fig. 10). At distances within a kilometer of the RFGF, the potential temperature was approximately 1 K lower than the maximum at 5 km. Surface observations collected rearward of the RFGF suggest that the wake and RFIS noted in the UAS data were also present at the surface. However, these features appeared differently at the surface rather than aloft. An initial drop of \( \sim 1 \) K was recorded as the RFGF crossed the StickNet array (Fig. 10). Rearward of this initial cooling, the potential temperature measured by the StickNet increased by 1–2.5 K with respect to values before RFGF passage, reaching a maximum at approximately 5 km behind the primary gust front, near where the warming observed by the UAS began but before temperatures aloft reached their maxima (Figs. 8 and 10). The StickNet potential temperature north of 39.67°N recorded local maxima in potential temperature within the RFO closer to the RFGF. In contrast to potential temperature aloft, the StickNet-observed potential temperature in the wake at the surface exhibited a single maximum (Fig. 10). In general, as measured by the southern branch of the StickNet platforms, the potential temperature increased by 0.5–2 K in the 2.5–9-km range rearward of the RFGF (Fig. 10). Corroborating this finding, the PSU mobile mesonet also observed a local maximum in potential temperature near 39.67°N (Fig. 11). StickNet platforms along and north of 39.65°N recorded a rapid drop in potential temperature between 5 and 10 km rearward of the RFGF. This decrease in potential temperature was likely tied to the RFIS encountered by the UAS. The PSU mobile mesonet encountered a more gradual decrease in potential temperature north of 39.70°N, suggesting that the RFIS may not have been as well defined in the northern RFO, or may not have existed at all.

The increase in potential temperature from the primary RFO rearward to the wake was not as rapid as the subsequent cooling in the RFIS. This could be explained by warm air from aloft mixing with air in the primary RFO such that air temperatures only gradually warm as the wake approaches, which would be consistent with the warm air being advected into the outflow through the wake. The larger temperature gradient between the wake and the RFIS may have existed as a result of kinematic frontogenesis in this region, whereas the temperature gradient behind the RFGF may have been weaker as a result of surface kinematic frontolysis. Frontogenesis and frontolysis will be discussed further within the context of the observed wind field below.

Temperature data collected by the scout mesonet (which collected similar measurements to the PSU mobile mesonet) exhibited the same basic patterns as those represented in the StickNet data with a distinct warming near 5 km rearward of the RFGF and a strong cooling farther back into the outflow (Fig. 12a). Scout mesonet water vapor mixing ratio observations exhibited some similarities to those collected by the UAS: the RFO was generally drier than the pre-RFGF air mass (Fig. 12b). Compared to pre-RFGF air, air within the wake region...
was generally drier near the surface than aloft during the first traverse. The RFIS was relatively moist compared to the rest of the RFO and the inflow (Fig. 12b). Interestingly, the second traverse through the wake region executed by the scout mesonet revealed slightly higher $q_v$ (Fig. 12b) perhaps due to differences in data collection time.

Surface wind speed and direction data collected by StickNet and the mobile mesonet were analyzed within the same RFGF-relative reference framework as the thermodynamic observations. StickNet observations showed generally easterly or northeasterly ground-relative flow in advance of the RFGF (Fig. 13). Winds then shifted to a more westerly or northwesterly direction with the passage of the RFGF. At all but the farthest north StickNet stations (Fig. 13), winds shifted back to easterly and northeasterly between 4 and 6 km rearward of the RFGF. The southern StickNet stations maintained an easterly wind component during the remainder of the analysis period. Two of the northern StickNet stations measured shifts to northwesterly flow at about 10 km rearward of the RFGF. The potential temperature decreased, coinciding with the northwesterly wind shift, supporting the wind shift’s connection to the cold RFIS. Kinematic observations from the scout mesonet and PSU mobile mesonet generally corroborated the wind field inferred from the StickNet data (Figs. 11 and 14).

The wind field measured by StickNet suggested that an area of diffluent flow existed approximately 3–6 km rearward of the RFGF, where winds shifted from northwesterly to northeast or east-northeast. This region of surface diffuence suggests that a downdraft may have been present 3–6 km rearward of the RFGF. However, farther to the north in the RFO, this diffluent pattern was not present. Rather, winds remained west-southwesterly until a shift to northwesterly winds occurred at ~11 km behind the RFGF (refer to the observations from the StickNet pod near latitude 39.70°N in Fig. 13 as well as the observations north of latitude 39.68°N from the PSU mesonets in Fig. 11). Thus, a possible downdraft extending to or near the surface in the wake was not ubiquitous from south to north through the RFO, but instead was favored in the southern portion of the RFO. As noted above, this pattern of diffuence within the wake and confluence at the RFISB (Fig. 13) could be in part responsible for the larger, frontogenetic, thermodynamic...

FIG. 12. Traces of scout mesonet (a) potential temperature and (b) water vapor mixing ratio. The blue dashed line represents the drop in potential temperature associated with the RFIS, while the red dashed line denotes the beginning of the outflow wake at the surface. Data immediately rearward of the RFGF were removed because of the failure to pass automatic quality control checks.

FIG. 13. Ground-relative wind. As in other figures, the blue line at distance = 0 represents the RFGF. StickNet platforms that had flagged wind speed or direction were not included. The blue dashed line denotes the beginning of the RFIS, and the red dashed line shows the beginning of the outflow wake at the surface.
gradient in place along RFISB and generally more relaxed, frontolytic, thermodynamic gradient near the transition to the wake air mass.

The shallow volume scans of NOXP captured some of the vertical and horizontal flow structure within the RFO, especially from about 0158 UTC onward, when the RFGF was close enough to NOXP that the vertical structure of the gust front head and flow structure to its west could be examined. A few prominent features within the RFO flow field become apparent when viewed in range–height plots derived using six elevation tilts (2°–7°; tilts at 1° elevation were excluded because of extensive missing data). First, the RFO possesses an elevated head to the south of the hook echo (as indicated by inbound radial velocity; Figs. 15a–c). Second, an extensive area of outbound radial velocity was found rearward of the RFO head (at the same altitude as the inbound velocity at the RFGF). Third, the depth of the inbound radial velocities, which is likely associated with the depth of the RFO, increased from south to north. For example, at 0200 UTC (Fig. 15a), the inbound winds south of the hook appeared to extend to roughly 0.8 km AGL at its highest point, whereas the inbound winds appeared to exceed 1 km closer to the hook echo; this pattern continued over the 0200–0208 UTC period (Figs. 15a,b). Fourth, in areas of shallower RFO, a region of radial divergence (yellow boxes in Fig. 17) was found at the rear of the elevated outflow head. This area of radial divergence is consistent with the in situ observations of surface diffuseness and the inferred attendant downdraft, which could advect and mix inflow air (located above the RFO) with RFO air. The presence of outbound radial velocity in the wake and at the top of the RFO suggests that winds in these regions had an easterly component, given NOXP’s location to the east of the RFGF. Finally, these features were persistent: they were found in all volumes covering a 10-min period. The persistence of these features also lends confidence to the assumption that the UAS and surface-observing platforms encountered the structures seen in NOXP data, much of which was collected between 5 and 15 min after the in situ data collection periods presented previously.

4. Discussion

The above analysis of the RFO of the Last Chance, Colorado, supercell indicates that the observed thermodynamic and kinematic inhomogeneities could be attributable to the mixing of relatively warm inflow air into the RFO through turbulent mixing “behind” the leading portions of the RFO. This behavior would be consistent with the well-established model of mixing within the wake behind the head of a density current. Density current wakes are in part attributable to KHI, a shearing instability that exists near the upper interface of many density currents (Simpson and Britter 1980; Simpson 1997). Given the low vertical resolution of the NOXP data and a lack of full three-dimensional wind components aloft, the Richardson number was not estimated, as had been done by previous studies (e.g., Browning and Watkins 1970; Yamamoto et al. 2003). However, given the vertical shear in the NOXP radial velocity (Fig. 15) it is probable that KHI was supported. Consistent with prior observations and simulations of density currents (e.g., Simpson and Britter 1980; Droegemeier and Wilhelmson 1987; Xue et al. 1997; Geerts et al. 2006; Limpert 2013), large KHI billows rearward of a density current head can mix thermodynamic and kinematic properties of the surrounding environment into the density current.

The observed turbulent wake was found to extend, at least periodically, to the ground, modifying or replacing portions of the RFO trailing leading edge of the outflow. However, while this seems to have occurred within southern parts of the RFO, farther north (immediately south of the hook echo) this structure was not observed. The southern RFO appeared to have been shallower than near the hook echo, which could make it easier for “warm” parcels to penetrate through the (cool) outflow to the surface. A possible explanation for why the RFO appeared to be shallower in its southern extent is that, simply, the outflow was farther from its source (Liu and Moncrieff 1996).

While thermodynamic observations support the presence of an RFIS, kinematic observations do not follow a model for any RFIS that has been presented previously. The definition of an RFIS introduced by Lee et al. (2012) requires at least a 13 m s⁻¹ increase in wind speed
FIG. 15. Vertical cross sections of radial velocity from NOXP. Cross sections are in pairs, from top to bottom, at (a) 0200, (b) 0204, and (c) 0208 UTC. Yellow dashed box represents region of radial divergence.
associated with the RFIS. However, the winds in the RFIS observed herein increased by only 5 m s$^{-1}$ and were principally manifested as a wind shift. The observed wind field manifestation of the RFIS is consistent with an RFIS that is not a "surge" in the RFO per se, but the trailing portion of the RFO that has been at least partially separated from the outflow head by the wake. This appears to be further supported by the observation that in northern portions of the RFO neither an RFIS nor a wake were observed.

Similar to RFISs fitting the Lee et al. definition, the RFISB observed here was characterized by confluence and likely convergence; recall that the observed RFISB was capable of producing a strong leading-edge updraft, consistent with strong low-level convergence and associated pressure perturbations at this boundary. Thus, the observed wake airflow supported kinematic frontogenesis at the interface between the rear of the wake and the RFIS, where the easterly flow shifted to westerly or northwesterly flow.

The hypothesized role of KHI-driven mixing in producing the RFO heterogeneity observed within the Last Chance supercell is consistent with observations and simulations of atmospheric density currents. It is also consistent with the proximity environmental conditions. In a set of model simulations investigating the effects of thermal stratification on the density current structure, Liu and Moncrieff (2000) found that low-level static stability within the inflow ahead of a density current can increase the penetration of inflow air into a cold outflow. Moreover, previous studies have found that low-level shear plays a role in regulating the density current depth (e.g., Xu 1992; Xue et al. 1997). Specifically, all else held constant, a density current should be shallower if the low-level environmental shear vector is directed toward the cold air. A shallower outflow should be more likely to allow deep downward penetration of inflow air into the outflow. Furthermore, when the environmental shear vector is directed toward the cold air, larger and deeper Kelvin–Helmholtz billows are supported (Xue et al. 1997). For the Last Chance supercell, vertical thermodynamic profiles through the lowest 350–400 m of the storm inflow collected by the UAS during launch revealed an approximate vertical potential temperature gradient of 2.37 K km$^{-1}$. Wind data from the three soundings launched to the east of the supercell (refer to Fig. 2 for the locations of the soundings) revealed that the RFGF-normal component of the vertical shear$^2$ within the lowest 750–1000 m of the inflow layer was generally negative (Fig. 16); that is, the low-level shear vector was pointed toward the cold side of the density current. Ultimately, both the inflow static stability and vertical shear of this event should support a density current with

\[ U \text{ component of wind (m s}^{-1}\text{)} \]

\[ a) \text{ U-component of Wind From 013720 Sounding} \]

\[ b) \text{ U-component of Wind From 013848 Sounding} \]

\[ c) \text{ U-component of Wind From 014013 Sounding} \]

FIG. 16. The $U$ component of wind (m s$^{-1}$) from (a) 0137, (b) 0138, and (c) 0140 UTC soundings.

\[^2\text{Since the RFGF orientation was largely north–south, the vertical profile of the } u \text{ component of the inflow winds is used to represent the RFGF-normal component of the shear.} \]
KHI-driven mixing that penetrates toward the surface. In addition to KHI-driven mixing, it is possible that a different downdraft mechanism may have been important in leading to relatively warm air and diffuent flow being found at the surface. However, based on the low-level (500–1000 m) origins of air inferred from the discussion of Fig. 9, a downdraft by another mechanism would need to draw primarily low-level air to the surface. One possibility could be a downdraft forced by a high pressure perturbation owing to flow stagnation above the density current (similar to a mechanism proposed for an RFIS in a simulation of the 8 May 2003 supercell) (Schenkman et al. 2016). Unfortunately, given that dual-Doppler synthesis could not be performed for this case, it is difficult to assess the likelihood that this mechanism was relevant.

As discussed in section 1a, RFISs have been hypothesized to aid in tornadogenesis and tornado intensification because of their ability to provide increased surface/near-surface convergence within an established RFO. The surface convergence associated with an RFIS boundary forming as proposed here could serve the same function. However, an important caveat exists when trying to attribute an increased likelihood for tornadogenesis or tornado intensification to the presence of an RFIS boundary formed by this mechanism. This process is more likely to occur away from sources of cold air (i.e., well south of the hook echo). Thus, convergence along a secondary boundary forming as hypothesized herein would seem unlikely to impact the surface circulation center near the hook unless the RFO is uniformly shallow.

Independent of whether or not the resultant RFIS boundary could aid in tornadogenesis through stretching, the presence of relatively warm air in the RFO is also potentially important for tornadogenesis. The associative relationship between the cold pool buoyancy and tornadogenesis (Markowski et al. 2002; Grzych et al. 2007; Hirth et al. 2008; Lee et al. 2012) may be attributable to the resistance of negatively buoyant air within the cold pool to vertical acceleration (Markowski and Richardson 2014). Thus, an RFO warmed through advection/mixing of inflow air in a penetrating wake circulation could substantially reduce the stability of the RFO air near the surface circulation. Can the mixing of warm air into an RFO through the outflow wake result in warm air residing near the surface circulation, thus increasing the likelihood of tornadogenesis? For the Last Chance supercell, easterly ground-relative momentum was only found at the surface in southern portions of the RFO, and the warming in the wake of the RFGF was tempered or nonexistent north of ~39.7°N. This was hypothesized to be a consequence of deeper outflow to the north near the hook echo. Thus, the outflow would need to be shallower for the wake circulation to advect inflow air into the RFO near the circulation center. Alternatively, warm air in the wake farther to the south could be advected northward toward the mesocyclone by winds with a strong southerly component in the RFO. This would require inflow with a more southerly storm-relative wind component than existed in this case.

5. Conclusions

The Tempest unmanned aircraft system, NOXP mobile radar, StickNet, scout mesonet, and several Pennsylvania State University mobile mesonet probes sampled the rear flank outflow of the 10 June 2010 Last Chance, Colorado, supercell during a posttornadic phase. The suite of observing platforms sampled the inflow air mass (ahead of the rear-flank gust front), the rear-flank gust front, a turbulent wake within the rear-flank outflow, and a rear-flank internal surge over a ~36-min span. The following tentative conclusions emerge from analysis of these data and are conceptualized in Figs. 17 and 18:

- The warm, dry air found 4–9 km rearward of the southern sections of the RFGF was a consequence of mixing of inflow (pre-RFGF) air into the RFO within the wake circulation rearward of the RFO head (Figs. 17 and 18). This mixing may have been driven in part by the release of KHI.
The depth of the downward penetration of the wake circulation decreased with increasing latitude: farther north (near the hook echo), the RFO showed little indication of this wake circulation. This inability of the wake circulation to penetrate the RFO farther north may have been a consequence of a deeper initial RFO near the precipitation (the source of outflow air).

The inflow vertical shear and static stability favored a density current with KHI-driven mixing that penetrated toward the surface, which may have played a large role in modifying the kinematic and thermodynamic character of the RFO at the surface.

The RFIS appeared to manifest as the arrival of the trailing RFO rearward of warming associated with the outflow wake (Fig. 18). The RFISB is clearly apparent in the observations and the associated convergence and attendant above-ground vertical motion was significant. This was likely attributable to amplification of the temperature gradient through confluence ahead of the RFIS. This confluence was a direct response to the mixing of inflow air into the RFO within the wake. Thus, the wake mixing not only may have produced the RFIS, but could have amplified the attendant boundary.

Since much of the thermodynamic analysis presented was based on data collected by either stationary (StickNet) platforms or instruments that only performed a single transect through parts of the RFO (UAS and scout mesonet), no attempt was made to diagnose the temporal variability in the thermodynamic and kinematic RFO characteristics. As a result of the persistence of the radial velocity structures present in NOXP observations, it is inferred that an elevated head, deep wake, and secondary outflow structure were ubiquitous across at least the last 10–15 min of the period of study. However, the observations (both radar based and surface/UAS in situ data) are not sufficient to determine whether the outflow head was fully separated from the secondary outflow surge for the entire period of study, or across the entire inferred wake region of the RFO at any particular point in time.

The data used were also unable to reveal the effects that warmer air in the RFO may have had on the evolution of this particular supercell.

To the authors’ knowledge, relatively warm air in RFOs has not been previously attributed to the effects of Kelvin–Helmholtz billows in RFO wakes. However, it does not necessarily follow that the process described above is unusual in supercells, though it may be less common closer to the precipitation or in inflow environments with less static stability or “less favorable” vertical shear. The extent to which it is common for 1) relatively warm air to entrain into RFOs via density current dynamics or 2) a cold RFIS to form by this mechanism will require additional surface and above-ground observations within supercell RFOs.

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