Details of Colliding Thunderstorm Outflows as Observed by Doppler Lidar

J. M. Intrieri

Cooperative Institute for Research in Environmental Sciences, University of Colorado/NOAA, Boulder, Colorado

A. J. Bedard, Jr. and R. M. Hardesty

NOAA/ERL/Wave Propagation Laboratory, Boulder, Colorado

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ABSTRACT

Three cases of colliding outflow boundaries are examined using data collected from the NOAA Doppler lidar and a meteorological tower during the summer of 1986 near Boulder, Colorado. The data are unique because the lidar and the 300 m tower were colocated, providing measurements of both kinematic and thermodynamic properties. Lidar data reveal small-scale vortex roll instabilities within the leading edge of the outflow. Observations of the post-collision interactions showed that the warmer of the two outflows was deflected upward by the colder outflow to heights of 2 km. In all cases, this forced mechanical lifting was sufficient to produce convection. A simple model of two colliding density currents also suggests that deeper outflows are more efficient in initiating convection.

I. Introduction and background

A mature thunderstorm releases a cold downdraft that diverges on the surface and moves away from the parent storm. The outflow, driven by the cool, dense air behind its leading edge, or gust front, advances along the ground, lifting less dense boundary layer air over the gust front as it propagates. Many studies have shown that a thunderstorm outflow is similar to a density current in structure and dynamics. Simpson (1969) demonstrated this using water tank experiments, and most recently Droegemeier and Wilhelmson (1987) showed this similarity using numerical models. Field observations (e.g., Mueller and Carbone 1987; Wakimoto 1982) using Doppler radar have also shown the similarities between density currents and thunderstorm outflows.

Vertical air motion is associated with the leading edge of a single outflow. When two outflows intersect, the vertical extent of the upward forcing is even greater. Droegemeier and Wilhelmson (1985) modeled cloud development along intersecting thunderstorm outflow boundaries and showed that strong updrafts, caused by the collisions, create an enhanced region for mesoscale convection. Although satellite (Purdom 1976) and radar (Mahoney 1988) studies have documented the connection between colliding outflow lines and mesoscale convection, important details have not been measured, and questions concerning convective initiation remained unanswered.

Very little information exists on the small-scale interactions of colliding outflows. Although strong updrafts and circulations occur when outflows collide, defining the collision details presents a difficult measurement problem. Colliding boundary dynamics pose many questions. For example, why do some boundaries continue to propagate after a collision whereas others do not? How are the updrafts oriented? This paper addresses those questions as well as others related to the dynamics of colliding outflow boundaries, using data from the Mesogamma 86 field experiment. The Mesogamma 86 experiment (Phase II) was conducted by the Wave Propagation Laboratory (WPL) of NOAA during the summer of 1986 in northeastern Colorado (Bedard et al. 1988). The experiment was in part designed to study mesoscale interactions with the small-scale, (micro-alpha and -beta, 4000 m — 40 m; Fujita 1981) circulations of gust fronts, microbursts, and thunderstorms. A ground-based Doppler lidar and Doppler radar operated in close proximity to a meteorological tower. Also, data from radiosondes, surface sensors, a mobile observing system and a variety of other sensors were available. Our investigation applied the Doppler lidar’s clear-air scanning capabilities to investigate colliding outflows (Intrieri et al. 1988).

Our data help to fill a gap in previous observational studies that were limited by sensor resolution on horizontal and vertical wind fields. Using lidar data along with the thermodynamic support from a 300-m tall meteorological tower, we were able to study the prop-

Corresponding author address: Janet M. Intrieri, CIRES, University of Colorado/NOAA, Boulder, CO 80303.
agation, collision, and interaction of low-level boundaries. It is important to make the distinction between interacting versus colliding outflow boundaries. We use the term collide to identify the initial contact between two boundaries. We use the term interaction when speaking of subsequent motions. In the cases we observed, the boundaries had already collided but continued to interact within our observing area, influencing each others propagation characteristics.

We examine the kinematic and thermodynamic fields for three case studies of colliding outflow boundaries. We compare similar features such as horizontal rolls, as well as differences observed between the cases, such as collision dynamics and resulting patterns of convection. We also present a theoretical analysis of two (identical) colliding density currents to obtain additional insight concerning density current details affecting outflow interactions.

2. Data sources and analysis techniques

Mesogamma 86 (Phase II) was centered at the Boulder Atmospheric Observatory (BAO) in Erie, Colorado (Kaimal and Gaynor 1983). Information on the vertical thermodynamic structure of the lower troposphere was provided at 0.1 s intervals by the BAO tower; balloon soundings also were released on request at the site. The NOAA-C Doppler radar (3-cm wavelength) supplied information on locations and radar reflectivities of convective cells. The outflow boundaries, propagating away from parent storms, were identified and tracked through the observing area using the Doppler lidar real-time displays of velocity and intensity fields. This lidar real-time display capability became the primary tool for guiding the experiment.

The lidar, a coherent laser-based remote sensing system, is similar in principle to a Doppler radar. The differences, however, make lidar an especially valuable tool for studying outflow boundaries. The lidar senses the radial wind speed from the movement of aerosols suspended in the atmosphere (Lawrence et al. 1983). The small size of the scatterers, typically 1–3 μm in diameter, makes lidar a clear-air sensor that does not rely on water droplets, insects, etc., for a return signal as do many microwave Doppler radars. Because the laser beam is collimated (beam diameter is less than 1 m), there are no sideline effects; beam-spreading effects are also minimal. Therefore, unlike most radars, lidars are not subject to ground clutter when scanning close to the surface. The narrow beam provides the potential for a transverse spatial resolution of 2 m at the limit of the horizontal range, which is typically 25 km.

Taking advantage of this high azimuthal resolution, we interpolated lidar radial velocity measurements onto a Cartesian grid using a distance-dependent Cressman (1959) weighting function processed in the Overdetermined Dual Doppler Analysis routine, ODDAN (Kessinger et al. 1987). Since the radial velocities contain contributions from both the vertical and horizontal wind components, we used elevation angles below 30° to minimize the vertical wind contribution. Grid spacing was 50 m in the vertical and 300 m in the horizontal. Vertical resolution is 5 times greater in this data set than in previous radar analyses of gust fronts because of the resolution afforded by the narrow laser beam. The wind speeds were further processed using a two-dimensional form of the continuity equation to obtain estimates of the vertical velocity fields (Mohr et al. 1986):

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} + \frac{1}{\rho} \frac{\partial \rho}{\partial z} w = 0. \quad (1)$$

All symbols have their usual definition and $\rho$ refers to the air density. We assumed that the longitudinal diffusivity along the radial can be ignored and that the variation of density with height is negligible (Wakimoto 1982). All lidar range height indicator (RHI) scans used to construct the vertical cross sections only deviated from the normal to the front by at most a few degrees. Therefore, we assume the Doppler velocities are a very close estimate of the horizontal wind speeds. An upward integration of the anelastic continuity equation provides vertical velocities under the assumption that $w = 0$ at the surface. The resulting products should be applied with caution since the flows can be highly three-dimensional, and serve best to illustrate the basic kinematic features associated with outflow boundaries such as roll vortices or waves.

3. Case histories of colliding outflows

Three colliding outflow cases observed at the BAO are described below. Subsequent analyses discuss the kinematic and thermodynamic details based on examples from these three cases. Diagrammatic overviews of each case, composed from lidar and radar scans, are depicted in Fig. 1. The velocities in the associated lists of variables have been adjusted to be relative to the estimated, undisturbed velocity field in order to facilitate comparison of the outflows.

In cases 1 and 3 each outflow that was involved in a collision propagated past the tower so that temperature, windspeed, and pressure were known. For case 2 we inferred missing variables from density current parameters using the gravity current equation (Prandtl 1952):

$$u = Fr[(\Delta T/T)gh]^{1/2}, \quad (2)$$

which allows a quantitative comparison between the density current details and outflow boundary speeds. In Eq. (2), $h$ is outflow body depth, $u$ the observed propagation speed, $g$ gravitational acceleration, $T$ temperature of the medium, $\Delta T$ the temperature difference between the outflow air and the medium, and $Fr$ is the
Fig. 1a. Overview of case 1 depicting distance between parent thunderstorms and the leading edges of their respective outflows at different times (UTC). Collision occurred at 2315 UTC. Shaded region depicts the location of the first cell resulting from the collision as detected by the NOAA-C Doppler radar at 2335 UTC. Line AB represents lidar RHI orientation. Variables are listed on the right, above a vertical cross section of the collision based on lidar RHI scans along line AB.

Fig. 1b. Overview of case 2, as in Fig. 1a. Collision (dash-dot line) occurred at 2201 UTC just east of the lidar.

Fig. 1c. Overview of case 3, as in Fig. 1a. Collision occurred southwest of the lidar at approximately 2123 UTC.
Froude number, which is the nondimensional ratio of inertial to gravitational forces.

a. Meteorological observations for case 1

On 4 August 1986 a small thunderstorm line, 15 km west of the lidar, produced an outflow boundary that propagated at 7 m s\(^{-1}\) toward the Mesogamma 86 site. This outflow collided with another boundary that originated in a thunderstorm cell 25 km to the east. The collision occurred at 2310 UTC just west of the tower and was scanned by the lidar in Range Height Indicator (RHI) mode along the line labeled AB in Fig. 1a. The colder, westerly outflow ducted beneath the eastern boundary, deflecting it up and over to the opposite side (past the collision point). Lidar scans, taken up to 13 minutes after the initial collision, revealed that the westerly outflow continued to strongly propagate eastward while the easterly outflow descended on the opposite side, weaker yet remaining intact. This leads us to conclude that the two outflows collided, passed one another, and continued to propagate along their original bearings. Approximately 30 minutes after the collision (2340 UTC), convection occurred over the observing area as depicted by the shaded region in Fig. 1a. The cells reached a maximum reflectivity of 40 dBZ and produced moderate rain at the site. Past observations of intersecting radar fine lines (e.g., Boyd 1965) show similarities to the boundary interactions we observed. Rider and Simpson (1969) detected radar fine lines from a seafreeze front and a thunderstorm outflow boundary that intersected and then continued to propagate along their initial paths. Using water tank simulations, Simpson (1987) found that after two currents collide, a hydraulic jump reflection results in the form of an undular bore, and he did not observe density currents to actually “cross” for the water tank simulation conditions he used.

b. Meteorological observations for case 2

The second event, on 24 July 1986, exhibited flow interactions quite different from those in case 1. The overview of the event in Fig. 1b depicts the thunderstorm outflows colliding just east of the tower at 2201 UTC. The cold shallow, east-southeasterly flow, propagating at 7 m s\(^{-1}\), advanced to within 4 km of the tower. At this location it became stationary, creating a barrier to the deeper northwesterly outflow and deflecting this advancing air mass upward as much as 2 km AGL for a period of more than 20 minutes. Lidar RHI scans along the line AB (Fig. 1b) showed the easterly outflow finally eroding away under the stronger northwesterly winds. The forced upward motion resulting from the collision produced a small line of clouds just east of the BAO. The shaded region in Fig. 1b depicts the location of the cells that formed parallel to the collision line at 2222 UTC and reached a maximum reflectivity of 45 dBZ.

c. Meteorological observations for case 3

A thunderstorm outflow from a small 45 dBZ cell, 15 km to the southwest, moved rapidly toward the BAO as depicted in Fig. 1c. The thunderstorm system spanning from northwest to northeast produced a large outflow region with very vigorous winds. As these two outflows collided south of the tower, the colder southwesterly air mass lifted the northerly outflow as it continued propagating northward. This interaction initially resulted in cloud development perpendicular to the collision line. Within 10 minutes, a 20-km-square region was filled with thunderstorms that reached intensities of 50 dBZ, eventually producing heavy rain and small hail at the BAO site.

4. Analysis of outflow structure

a. Collision kinematics

A diagrammatic view of two thunderstorm outflows approaching each other is shown in Fig. 2. The common names given to the features of a density current (Simpson 1969) are labeled as they are referred to throughout the text. At the foremost part of the density current is the gust front or leading edge where a nose, which is slightly raised above the ground, is located. The leading edge is the raised head that is higher than the following flow or body. In the head region there often exist circulations or vortex rolls associated with greater internal horizontal velocities than the mean propagation speed of the current. The arrows represent motions likely to result when two currents collide, the warmer air mass overriding the colder, denser air. Each of the collisions we observed followed this pattern.

Lidar RHI scans for the three cases are pictured in Figs. 3, 4, and 5. The void of data in the middle of all scans indicates the lidar minimum range of about 1.5 km. This is due to saturation of the lidar receiver by returns at short ranges.

The lidar RHI radial velocity scan for case 1 (Fig. 3) was taken at 2318 UTC, approximately 8 minutes after the initial collision, and shows the shape of the westerly outflow boundary as well as the deflection of

![Fig. 2. Diagrammatic view of two approaching thunderstorm outflows approaching, labeled with common names given to typical features of density currents. Bold vectors depict the resulting interactions after collision, the colder outflow deflecting the warmer one upward.](image-url)
the easterly outflow over the top. The orientation of the updraft air conforms to the shape of the denser outflow displacing it. The slope of the outflow leading edge is partly determined by its velocity and the velocity of the opposing flow. Thus, an outflow propagating into stronger winds will exhibit a steeper head (Simpson 1972).

In this case, the easterly outflow is lifted up to the height of the westerly boundary. As the easterly flow descends on the opposite side, divergence appears at the trailing edge of the westerly outflow (located at −7 km) with a horizontal shear value of $5.2 \times 10^{-3}$ s$^{-1}$. Case 1 is a clear example of a boundary reaching the surface behind a vortex roll to produce a "divergent outflow," which could be mistakenly interpreted as weak microbursts or lines of microbursts, since the Doppler signatures are practically identical.

The sequence of lidar scans for case 2 (Fig. 4) shows the stationary easterly boundary deflecting the much deeper, opposing outflow upward to heights of 2 km. This upward forcing continued for more than 20 minutes. Note the change in the profile of the easterly boundary between the first scan taken at 2158 (Fig. 4a) and the last RHI of the sequence at 2209 UTC (Fig. 4c).

In case 3, the outflows collide at a region within the minimum range of the lidar. Notice in the first scan of the sequence (Fig. 5a), taken at 2148 UTC, that flow is approaching the lidar from both sides at approximately 12 m s$^{-1}$. Most striking about this scan is the direct measurement of the vertical velocities provided by the radials near the 90° elevation angle. A large region of upward motion of $\sim 5$ m s$^{-1}$ exists from −1.0 to 4.0 km horizontally, and up to 3.0 km above the outflows. In scan two (Fig. 5b) the steeply-sloped head, reaching 2 km in height, has just propagated toward the westerly half. By 2153 UTC (Fig. 5c) a complete profile of the head region pushing back the opposite outflow is evident.

b. Roll vortices and instabilities

Previous studies (e.g., Wakimoto 1982) investigating the nature of density currents, microbursts, and outflow boundaries have observed horizontal role vortices at the leading edge of the gust front. These circulations or instabilities develop in regions of strong shear between two fluids. In all the cases presented here, roll vortices were evident from both the lidar-derived vertical cross sections and the BAO vertical wind data.

1) Lidar vertical cross sections

Figures 6, 7, and 8 show velocity cross sections from each case, computed from the radial velocity fields using continuity analysis. The solid lines denote the kinematic boundary where the transition zone between the outflows occurs, estimated from continuity and from the velocity vectors.

In case 1 (Fig. 6), a closed vortex roll is evident at the upper boundary of the colder outflow. This roll acts to lift the warmer air mass over the top. The vertical shear in this roll was $2.9 \times 10^{-2}$ s$^{-1}$. This represents
FIG. 4. As in Fig. 3, for a sequence of lidar radial velocity (m s⁻¹) scans for case 2 along the cross section indicated in Fig. 1b. Scan times: (a) 2158, (b) 2200, and (c) 2209 UTC. Negative velocities represent the wind component toward the lidar. The dashed lines show separation of air masses, and the arrows indicate direction of airflow.
Fig. 5. Sequence of lidar radial velocity (m s\(^{-1}\)) scans for case 3. Vigorous southwesterly outflow is shown here pushing back the northern boundary at (a) 2148, (b) 2150, and (c) 2153 UTC. Negative velocities represent the wind component toward the lidar.
shear that may pose a hazardous to low-flying aircraft. In these regions of strong shear between two fluids of different densities, Kelvin–Helmholtz instabilities (KHI) or vortex rolls may form at the interface. The Richardson number was calculated to be 0.11, just below the range where conditions allow KHI to develop. Richardson numbers were computed on the basis of temperature measurements from upper tower levels and horizontal wind shear as estimated from the lidar velocity data. Although some error is expected, these estimates should be more representative than the values based on surface temperature data only, used in previous studies (e.g., Mahoney 1988).

Mueller and Carbone (1987) showed that the kinematics vary within several kilometers along a gust front. Case 2 is an example of how dramatically the leading edge of an outflow can vary in shape and time. In the sequence of cross sections in Fig. 7, several small horizontal vortices have developed in the head region. The Richardson numbers for these smaller instabilities were estimated to be 0.5 or greater. Higher numbers signify that these vortices have broken down into turbulence at this stage, weakening the vertical shear layer. In Figs. 7b and 7c the slope of the head becomes steeper because of the increased velocity of the opposing outflow.

Case 3 shows the steepening of the head region even more vividly (Fig. 8). In this case the outflows propagate at nearly the same speed, and the upward deflections are practically perpendicular to the collision line. The vector fields show data only up to 1.75 km and do not reveal the full extent of the flows overriding one another above that height.

**Fig. 6.** A 180° vertical cross section for case 1, taken at 2318 UTC. The lidar is located at 0.0 km. The west half shows the vortex roll associated with the head of the density current. The solid line is an estimate of the kinematic boundary of the westerly outflow.

**Fig. 7.** Series of vertical cross sections for case 2, corresponding to times of lidar scans in Fig. 4. Solid lines are estimates of the kinematic boundaries of the easterly outflow. Note the smaller instabilities in the outflow and the changing profile of the outflow's leading edge. Lidar at 0 km.
horizontal wind velocity at the 200-m level of the BAO tower.

At the point where two fluids collide, the horizontal velocity is theoretically equal to zero, and a stagnation pressure is created. Such regions may be an explanation for the often observed "calm before the storm" (Wakimoto 1982). We can examine this stagnation pressure by using a modified form of Bernoulli's equation for steady, inviscid, and incompressible flow along a streamline:

\[
\frac{1}{2} \rho V^2 + P - g \rho \Delta z = P_0
\]

Dynamic pressure Static pressure Stagnation pressure

where \( V \) is wind speed in the cold air and \( \rho \) the density of the cold air.

The stagnation pressure \( P_0 \) is equal to the sum of the static and dynamic pressures. Therefore, as the parcel velocity approaches zero at the stagnation point, the pressure increases. Or rather, the pressure forces associated with the cold outflows can decelerate horizontal flows at the point of collision to create wind speed nulls.

d. Pressure

Absolute pressure data were available only for case 1 and we use this case to examine the pressure rise due to the passage of an outflow boundary. Both dynamic and hydrostatic pressure components contribute to the total pressure rise that occurs with a gust front passage.

2) BAO VERTICAL VELOCITIES

Roll vortices present in the leading edge of the outflows were also documented by the vertical velocity time series measured at the 200-m level of the tower in Figs. 10a, and 11a. Passage of the outflow leading edges is indicated by the shaded regions. In these cases, the large amplitudes in the vertical winds measurements reflect the rising motion ahead of and the sinking motion behind the roll.

Two separate roll features of equal amplitude reaching approximately \( \pm 2 \) m s\(^{-1}\) are obvious in Fig. 10 for case 2. In case 3, the upward- and downward-motion vertical velocities reached a maximum of \( \pm 4 \) m s\(^{-1}\) (Fig. 11b).

c. Horizontal wind speed

Before the actual gust front passed and the wind speeds increased, a null in the horizontal wind speed component \( u \) occurred in all the cases. This is shown in Figs. 9b, 10b, and 11b, which are time series for
The hydrostatic pressures are associated with the actual passage of the cold core and are most often preceded by the dynamic pressure component that is a result of the air masses colliding or a deflection of the streamlines (Bedard 1984). Figure 12 is a diagram of the outflow collision for case 1 along with the pressure trace. This estimates where the pressure was measured relative to the outflow’s location over the pressure sensor.

The calculated dynamic pressures for the combined flows at the point of collision is 0.03 kPa. The additional pressure rise, representing the hydrostatic component, occurred as the cold core propagated past the BAO and was calculated to be 0.08 kPa. Taking into account that both of these pressure components represent the total rise, we calculated a pressure increase of 0.11 kPa. This corresponds quite well to the observed pressure rise of approximately 0.10 kPa. The pressure fluctua-

5. Analysis of structure

Since all of the outflows collided within 5 km of the BAO tower, we were able to observe the thermodynamic properties of both pre- and post-collision environments.

All outflows exhibited the classic sequence of changes as they passed the tower. These changes were first noted by Charba (1974) who studied the vertical structure of a gust front. The typical changes observed by a meteorological station are a wind direction shift and pressure rise, followed by a wind speed surge, and a temperature drop. In most events, an outflow passage is followed by precipitation.

FIG. 10. Time series of BAO tower variables at the 200 m level for case 2 (a) vertical component of wind velocity, (b) horizontal wind speed and (c) temperature. Shaded region depicts passage of the northwesterly outflow leading edge.

FIG. 11. As in Fig. 10 but for case 3.

Thermodynamic characteristics of the outflows in this study were documented up to heights of 300 m as they propagated past the BAO tower. Times series of horizontal wind speed, temperature, and vertical velocities, recorded at the 200-m tower level, are shown in Figs. 9, 10, 11, for one outflow in each collision case. The shaded sections indicate when each outflow leading edge passed the tower. The outflows possessed similar thermodynamic characteristics.

**a. Temperature data**

A temperature drop occurred in each case as shown in Figs. 9c, 10c, and 11c. The colder, more dense outflow deflected the warmer outflow upward in every collision case we observed, making the warmer air mass the primary source of the updraft air. The temperature differences between the environmental air and the warmer easterly outflow in case 1 was 5.5°C. The colder westerly outflow, which deflected the easterly outflow, was an additional 2.5°C colder as depicted in Fig. 9c. In case 2 the easterly outflow, which remained stationary, did not propagate past the tower but was calculated to be approximately 4.5°C colder than the environmental air, assuming a Froude number of 1. Although this could be an overestimate of the temperature drop, the easterly outflow must have been significantly denser to deflect an outflow twice its depth. The opposing outflow, which was deflected upward, was only 1°C colder than the environmental air.

Case 3 is an example of two outflows similar in height and propagation speed but differing in temperature. The southwesterly outflow, which acted to push back the opposing flow, was 4°C colder.

A rapid warming occurred just prior to passage of the outflow’s cold core in cases 1 and 3 as indicated by the spike in temperature data in Figs. 6c and 8c. This may indicate that a shallow ground-based inversion was mixed out by the leading edge of the outflow (Mahoney 1988).

**b. Sounding data**

All collisions initiated new convection. We analyzed soundings, all launched at the BAO, (Fig. 13) to determine how high a parcel of air would need to be raised vertically to reach its lifting condensation level (LCL) and level of free convection (LFC). These two crucial heights dictate whether the lifted parcel will condense to first form a cloud and then, if lifted further, to rise spontaneously.

Figure 14 shows the Foote charts analyzed (Wilson and Mueller, 1987) for the two sounding days. The Foote chart (Foote 1984) gives the height (H) required for an air parcel to reach its LFC. The curve (L) esti-
mates the amount of forced lifting an air parcel will experience from a single density current of specified depth. Therefore, if \( L > H \), convection is likely. When \( H > L \), the atmosphere is considered stable. This method allows a quick evaluation of the amount of lift required to initiate convection in a certain environment.

Case 2 produced convection as the Foote chart predicted. However, the convection observed in case 1, which also initiated convective clouds, was not predicted by the Foote chart. This may indicate that buoyancy or momentum effects induced by collisions and not taken into account by the curve were important to the lifting process.

6. Initiated convection

In each case, echoes appeared on Doppler radar scans as a result of the outflow collisions. The first signs of convection in all cases appeared approximately 20 minutes after the collision and within 5 km of the collision line even though the orientations varied in each case. Wilson and Schreiber (1986) have also shown storms developed approximately 20–30 minutes after collision. (See Figs. 1a, 1b, and 1c for cell locations relative to the collision region.) In case 1, the initial convection was triggered approximately 7 km downstream from the collision line.

Case 2 initiated convection in a well-defined line parallel to the collision line. This is not surprising since a constant upward deflection of air existed at the same location for more than 20 minutes. The convection reached a maximum of 45 dBZ to produce moderate rain over the BAO site.

In case 3, special lidar scans indicated the locations of complex three-dimensional lobe and cleft structures and their relationship to the location of the convection. At the head of a gravity current, multiple shifting of lobes and clefts occur as it propagates along a horizontal surface. This is thought to be a result of gravitational instability (Simpson 1987). From lidar velocity azimuth display (VAD) scans, which traversed the southwesterly outflow in 1° “steps” from the surface to 12° in height, a distinct lobe was apparent (see Fig. 15). The head of the lobe is geometrically similar to those cited in laboratory studies by Simpson and Britter (1979). This upraised portion of the outflow most likely forced air higher and more effectively than nearby clefts as it propagated to create the initial line of convection normal to the collision. Approximately 20 minutes after the collision occurred, thunderstorms with reflectivities up to 55 dBZ filled in the entire 20-km-square area, producing rain and hail. Case 3 initiated the most severe convection, presumably because the outflows were deepest and associated with a more unstable environment.

7. A model of collisions between equal boundaries

Using a simple model we compare two equal outflows to evaluate theoretically the influences of outflow depth, temperature, and speed on the extent of vertical forcing and thus, on the likelihood of the initiation of convection.

The collision between two density currents is analogous to a downdraft impinging on a solid surface. Insights obtained from data on downdraft divergence can be used to guide an analysis of a boundary collision.

A two-dimensional jet impacting on a solid surface has been modeled as a jet approaching an image of itself. Prandtl and Tietjens (1934) have used this approach for computing jet/surface fields. For this situation the diverging real jet and its image jet (also diverging) combine to form two new jets, moving away.

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**Fig. 14.** (a) Foote chart for case 1. Dashed curve represents \( H \) and the solid line is \( L \). When \( L < H \), precipitation is not expected; however, rain was produced by this boundary collision. (b) Foote chart for case 2. Dashed curve represents \( H \) and the solid line is \( L \). When \( L > H \), convection is likely, and accordingly this collision produced precipitation.
that follows provides important insights into physical processes involved with density current collisions, and indicates a limiting case that should be useful for comparison with experimental data as well as theoretical and numerical results including additional variables.

a. Stage 1. Distant approaching density currents

In this stage the approaching boundaries, propagating through an unstratified, quiescent medium, are a distance of at least several scale heights away from each other and their motions are not disturbed, nor is the medium air at the collision point. Thus, the horizontal propagation speeds are calculated from the gravity current equation

$$u = Fr \left( \frac{\Delta \rho}{\rho} gh \right)^{1/2}. \quad (4)$$

This horizontal speed will be used in making an estimate of the vertical motion resulting from collisions.

These three stages are shown schematically as Figs. 16b, 16c, and 16d. In the analyses that follow we compute the propagation speed of the equal systems from the density current equation. The speed and dimensions are then used for specifying the initial conditions for a parcel in computing the penetration height of the density current air. The highly three-dimensional structure of outflow boundaries help to make this parcel representation realistic. There will be a continuing need to test the reasonableness of the approach and to develop guidelines for the choice of the height $h$ for “real” atmospheric outflows. However, the first-order analysis

![Figure 15](image1.png)

**FIG. 15.** Three-dimensional view of the radial velocities over 8 m/s reconstructed from lidar VAD sector scans taken at 1° elevation-angle intervals. All distances are in km.

![Figure 16](image2.png)

**FIG. 16.** Schematic views representing (a) collision of a density current with a wall, (b) two density currents of equal height and density differences approaching (c), colliding, and (d) moving vertically.
b. Stage 2. Collision

In this stage (since our idealized density currents are identical) the initial collision is similar to a downflow impacting a surface or a single density current approaching a wall. The image system causes the opposing flows to be zero at the midpoint boundary and in our case to move vertically. Bedard and LeFebvre (1986) found evidence that, for microbursts, the peak stagnation pressure and the outflow speed are related through Bernoulli's equation. We use this observation as the basis for assuming that 1) in the initial stages of a collision the horizontal flow speeds are diverted to the vertical and 2) the density current equation also indicates a value for the initial updraft speed. Since the density current air is cooler than the medium, the upward momentum provided by the collision must work against negative buoyancy forces. For this final stage we can estimate the extent of vertical motion.

c. Stage 3. Vertical motion

Although the medium air is also forced upward by the increasing pressure field between the approaching boundaries, it is probable that only a relatively small volume of lower boundary layer air moves upward with speeds approaching the vertical motion of the density currents. Also, typical dewpoints of moist density current air tend to be higher than the boundary layer air in which they are moving. This means that the LCL may be reached at lower atmospheric heights than boundary layer air when both are forced vertically.

In the analysis that follows, a parcel's initial vertical speed is computed from the density current equation. The parcel is assumed to move along a dry adiabat, maintaining the same temperature difference relative to the atmosphere as it rises. We follow the analysis of Scorer (1978) in estimating the resulting motion. Since for our system the buoyancy forces act to return a parcel to the surface, the second term in (5) and (6) is negative.

Using dimensional reasoning Scorer obtained an expression for the position of a parcel of buoyant fluid with an initial vertical speed $w_0$ as a function of time.

The vertical position

$$Z = (4N^3R_0^3)^{1/4} \left( w_0 t - \frac{1}{2} g \frac{\Delta T}{T} t^2 \right)^{1/4}, \quad (5)$$

where $N$ is a constant ($N = 2$) depending upon the relation between the dimensions of the parcel (or initial radius $R_0$) as a function of $Z$, and $t$ is the time. For $w_0$ we substitute $Fr(\Delta T/Tgh)^{1/2}$, setting $R_0 = h$, to obtain

$$Z = (4N^3R_0^3)^{1/4} \left[ \left( \frac{\Delta T}{T} gR_0 \right)^{1/2} t - \frac{1}{2} \left( g \frac{\Delta T}{T} \right)^{1/2} t^2 \right]. \quad (6)$$

This expression can be applied to studying the extent to which outflow air will penetrate vertically after a collision.

Figure 17a shows the time–height trajectories of air parcels from density current collisions for outflow heights of 0.25, 0.5, 0.75 and 1 km. For these cases the temperature decrease was $-5^\circ C$. The plots indicate a rapid increase in height as a function of time from the initial vertical momentum. The negative buoyancy forces slow the upward motion until the parcel finally reaches a maximum altitude and starts to return to the surface. At some altitude a change in state (condensation) could dominate the process and initiate new convection. These plots indicate that collisions involving larger gust front heights produce updrafts penetrating to higher altitudes.

When a density current height of 0.5 km is chosen, the time/height trajectories (Fig. 17b) indicate the position of a parcel as a function of time for temperature decreases of $-2.5$, $-5$, $-10$, and $-15^\circ C$. The maximum height to which the fluid penetrates is the same for all these density currents. However, the stronger density currents with larger temperature drops penetrate to a maximum altitude and fall to the surface again in a much shorter time than that required by weaker systems having small temperature drops.

The time, $t_{max}$ [computed from Eq. (6) for $dz/dt = 0$] that it takes a collision forced updraft to reach a maximum altitude is

$$t_{max} = Fr \left( \frac{R_0}{\frac{\Delta T}{T} g} \right)^{1/2}. \quad (7)$$

This relation indicates that shallow density currents will take a shorter time to penetrate to a maximum height. Figure 17c presents plots of $t_{max}$ as a function of $R_0$ for density current collisions having temperature drops of $-2.5^\circ C$ and $-15^\circ C$. The results also predict that the currents with smaller temperature drops take a significantly longer time to reach a maximum altitude.

The maximum height to which the parcel penetrates is found by substituting $t_{max}$ into Eq. (6) obtaining

$$Z_{max} = (4N^3R_0^3)^{1/4} R_0 Fr^{1/2}. \quad (8)$$

This expression predicts that the vertical penetration distance depends upon the height of the advection boundary and not upon the buoyancy forces that drive it (which also retard the vertical motion). Figure 17d is a plot of $Z_{max}$ as a function of $R_0$, indicating that for density currents of 1 km in height, the cooler fluid will penetrate to over twice its height as the result of a collision.

Systems with Froude numbers greater than 1 (typically $\sim 1.4$) will be most effective in initiating new convection. Such larger-than-usual values for Fr can occur near downflow regions where source region mo-
mentum dominates the buoyancy forces in the outflow boundary. Values of Fr > 10 have been observed (e.g., Bedard et al. 1979).

We performed an exploratory experiment using the simultaneous release of two equal volumes of saline solution into water. Condensed milk was mixed with the salt so that the density currents could be photographed as they approached and collided. Figure 18 shows the system at three differing stages: approaching, initial contact, and time of maximum penetration. These stages correspond well with the schematic views in Fig. 16. The currents penetrated vertically to a distance of about twice the precollision height, which is consistent with the estimate of Eq. (8). We recommend that detailed scale-model measurements be made of collisions, including different density currents over a range of parameters.

8. Implications for detection and warning of severe weather initiated by colliding boundaries

Because actual collisions involve many complicating factors, the results of our theoretical analysis do not consider many properties that could be significant. For example, leading edge gust front circulations could cause the vertical transport of density current air by mutual induction to heights greater than expected. The effects produced by turbulent diffusion are not explicitly included. We have already noted that the effects of condensation could at some point dominate the process. Also complexities introduced by gust front three-dimensionality (as evidenced by the lobe and cleft structures frequently observed), and interactions with the medium (e.g., shear layers of inversions) are not considered. Moreover, the Doppler lidar measurements presented here show the variety of interactions that can occur for “mismatched” boundaries.

The stability of the atmosphere through which the vertically directed gust front air moves adds an additional complexity. An inverse of this problem (downdrafts impacting a ground based inversion) has been considered by Bedard and LeFebvre (1984), who suggested that a Froude number criterion can be applied to estimate whether a microburst could penetrate to the surface through an inversion layer. Using a scale model this suggestion was subsequently validated by Young et al. (1989), finding that for Froude numbers <0.6 the microburst would not penetrate the inversion layer. For Froude numbers in its range from 0.6 to 1.2 the microburst would penetrate but not diverge. For
Froude numbers $>1.2$ the microburst penetrated the inversion layer, diverging at the solid surface beneath.

For each case of vertically forced flows from colliding thunderstorm outflow boundaries impacting a region of stable air aloft, a similar Froude number criterion can be applied. In this situation the difference between the density current air temperature and the temperature of the air within the stable region is used to define $T$. The height of penetration of interest is $h_p$, the penetration height through the stable air.

Thus, the penetration Froude number is

$$Fr_p = \left( \frac{\Delta T}{T} g h_p \right)^{1/2}.$$

We can estimate whether a vertically forced parcel of air can penetrate a given height through a region where it becomes more negatively buoyant. (Typically, a region above the top of the atmospheric boundary layer.) For the Colorado region Caplan and Bedard (personal communication, 1989) have summarized statistics showing that this level is typically about 2 km AGL, involving a temperature increase of 2ºC. Using the criteria found in water tank simulations, we can estimate that for Froude numbers $<0.6$, the system will not penetrate a distance greater than the system radius. For many practical situations, e.g., above the atmospheric boundary layer this will cause a small additional reduction in penetration height. Since the momentum driven updraft is often already cooler than its surroundings by 5º to 10ºC estimates of penetration height $Z_{\text{max}}$ will be approximately correct for most situations. If there is a strong capping inversion estimates could be made of the probability that the system will penetrate to some given height by applying the Froude number criterion [Eq. (9)] guided by the results of Young et al. (1989).

In spite of these limitations, insights from this analysis can indicate the likelihood of a collision’s initiating new convection if details are available from remote sensor and mesonet data concerning the approaching boundaries. The deeper density currents may be expected to penetrate to altitudes higher than those reached by shallow systems with larger temperature drops. Application of the Foote chart in estimating the
forcing of ambient air by density current views the outflow boundary as an obstacle. In contrast the analysis presented here views the vertical forcing as the result of an interaction between equal but opposing density currents. In our case the density current air is forced vertically. We view the two analysis procedures as different but complementary; Foote's analysis finding application to solitary boundaries and our analysis to interacting boundary situations. In some cases the ambient air may not be sufficiently moist to produce new convection when forced by a single outflow, whereas the dewpoints of two colliding outflows could permit strong convection to occur. We suggest the parallel testing of the two approaches.

The Doppler lidar is an ideal tool for evaluating the limits of validity of the theoretical analysis presented, and the region of the Boulder Atmospheric Observatory is an ideal location for performing measurements on colliding boundaries. There are frequent boundary interactions near the tower site, probably because of the plethora of convective generating regions in all quadrants relative to the BAO. The use of chaff at an expected collision point would provide valuable Doppler radar data. A thermodynamic profiler may be valuable for studying the evolution of the vertically forced air in the lowest 2 km.

In terms of three-dimensional effects we note that a collision between two gust front lobes will probably be most effective at producing strongly penetrating flows compared with a collision between two cleft regions. The relative locations of three-dimensional gust front structures may dominate detailed structure of lines of convection produced by interacting boundaries.

9. Summary

This study focused on three colliding outflow boundary cases and demonstrated the lidar's capability to observe the fine-scale features of thunderstorm outflows and boundary collision interactions.

Colliding boundaries are a key factor in mesoscale storm initiation. All the collisions in this study resulted in new convection. Upon colliding, the warmer of the two outflows was lifted over the cooler, denser boundary. The mechanical lifting was sufficient to lift air originating near the ground up to LCL heights.

The lidar clearly resolved large vortex rolls and smaller instabilities in the leading edge of the outflows. Observations of post-collision interactions provided information on the resulting convection orientation. A simple model evaluating the influence of certain outflow variables showed that deeper outflows are more likely to initiate new convection.

The Doppler lidar is an extremely valuable sensor for detecting atmospheric mesoscale dynamics. We hope that these data and our analysis will be helpful to researchers for further studies of flow collision dynamics in the atmosphere and to newscasters for evaluating such events in real-time situations.

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