Wind and thermodynamic profiler observations of a late-mature gust front

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High temporal and vertical resolutions of kinematic and thermodynamic characteristics of a late-mature gust front are presented using the Mobile Integrated Profiling System and Weather Surveillance Radar 88 Doppler data. As the gust front passed over the Mobile Integrated Profiling System vertical velocities and the horizontal wind field with 1 and 1.5 min temporal resolutions, respectively, were sampled within the gust front updrafts, gust frontal head and body structures. A 12-channel microwave profiling radiometer was used to delineate the thermodynamic properties with 5–6 min temporal and 100 m vertical resolution. Lidar backscatter from the 0.906 μm ceilometer was also used to demonstrate the cloud field and the gust front depth. The gust front structurally and dynamically resembled laboratory simulated density current, and was composed of an elevated forward protrusion of a nose, and a turbulent mixing region at the top behind the head. The updrafts associated with the gust front that was moving into a stable layer were not surface rooted. Rather, the updrafts less than 3.5 ms^{-1} were observed 500 m above ground level during the gust front passage. These updrafts were present from above the nose level to top of the head. The observations indicated that kinematic and thermodynamic characteristics of the atmospheric boundary layer significantly influenced the propagation speed, updraft characteristics, and overall structural organization of the gust front. The observations validated that observed propagation speed of the gust front was in close agreement with the calculated propagation speed by integrating the buoyancy term within the gust front depth.

1. Introduction

This study investigated comprehensive and detailed thermodynamic and kinematic characteristics of a late mature gust front passage and its interactions with the adjacent atmospheric boundary layer (ABL). The gust front (GF), an example of a convergent boundary zone (CBZ), is the manifestation of thunderstorm downdrafts driven by precipitation drag, and evaporative cooling. The horizontal pressure gradient due to the high hydrostatic pressure of the cold-dome is the energy source for the

GF (Wakimoto 1982; Weckwerth and Wakimoto 1992; Haertel *et al.* 2001). Wakimoto (1982) presented an analysis of different stages of life cycles of some GFs and defined the late-mature stage as being a density current, propagating under the influence of the greater hydrostatic pressure in the cold air, of which its source from the thunderstorm is almost depleted. A GF in its dissipative stage, on the other hand, is usually located far from a thunderstorm rainshaft and is no longer supplied with its cold air. Nevertheless, some GFs can propagate further distances without any apparent source of

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cold air from their emanated thunderstorms and can initiate convection if the atmospheric environments they propagate into are favourable. Therefore, the GF studied here was considered to be a late-mature GF in a sense that it structurally and dynamically resembled the density current simulations even though it was located 40–50 km from the nearest precipitating thunderstorm cells.

Land/sea breezes, thunderstorm outflows, and some shallow cold fronts are typical examples of atmospheric gravity currents (Simpson 1997). These types of mesoscale phenomena display very strong similarities with laboratory-simulated density currents (Simpson 1969; Simpson and Britter 1980). With the aid of high-quality surface-based remote sensing observations, the case investigated in this study makes it possible to evaluate whether or not a GF in a mature phase is dynamically and structurally similar to the laboratory simulated density currents. The Froude number (Fr) is frequently used for such dynamical similarity tests (Benjamin 1968; Simpson and Britter 1980; Atkins and Wakimoto 1997; Kingsmill and Crook 2003; Karan and Knupp 2009). In order to examine dynamical similarities between the GF and laboratory-simulated density currents, different formulations of Fr were examined. The Mobile Integrated Profiling System (MIPS) dataset provides direct measurements of vertical velocity and other crucial variables: the depth of a CBZ, virtual temperature deficit profiles, and horizontal wind field of the ambient flow and the flow behind the CBZs, which are important variables for Fr calculations.

Thunderstorm outflows and their GFs have been studied by means of observations, numerical modeling, and laboratory simulations. Data collected on the kinematic and thermodynamic structure of GFs from a 444 m tower (Charba 1974) revealed large wind and temperature gradients in the lower part of the frontal zone. Charba (1974) analyzed entrainment of environmental air in the wake of the gust frontal head and maximum low-level cold outflows beneath the head 175 m above the ground. However, spatial resolution and vertical extent of these types of phenomena require better observational techniques. Doppler radar observations, on the other hand, provide kinematic (two- and/or three-dimensional flow) information through the entire depth of the density currents. Wakimoto (1982), for instance, examined the life cycles of GFs using single Doppler radar and rawinsonde data. Mueller and Carbone (1987) used dual-Doppler radar analyses, surface mesonet, and sounding data to examine the outflow boundaries. They analyzed two updrafts separated with a downdraft within the gust frontal zone. Using a vertically-pointing X-band radar, Martner (1997) measured an abrupt

change from strong upward to strong downward motions just behind the GF. Utilizing continuous Radio Acoustic Sounding System (RASS) measurements of two GF events with a 915 MHz profiler, May (1999) described detailed structures of vertical motion and virtual temperature.

MIPS is capable of providing direct measurements of kinematic and thermodynamic variables with fine temporal and vertical resolutions to portray the vertical structure of CBZs (Knupp 2006; Karan and Knupp 2006, 2009; Coleman and Knupp 2011). Some of the past field campaigns such as CINDE (Wilson and Schreiber 1986), the COPS-91 and VORTEX programs (Ziegler and Rasmussen 1998; Rasmussen *et al.* 2000; Hane *et al.* 2002; Weiss and Bluestein 2002), the CaPE experiment (Wakimoto and Atkins 1994; Atkins *et al.* 1995; Wilson and Megenhardt 1997; Kingsmill and Crook 2003), and the IHOP-2002 (Weckwerth *et al.* 2004; Weckwerth and Parsons 2006) focused on the roles of CBZs on convection initiations (CI). Multiple Doppler radar analyses portray 3-D structures of CBZs and their role in CI, but they lack accuracy and high resolution in retrieved w fields. Dual Doppler radar analyses, for instance, can synthesize wind fields (u , v , w) with 2–5 min temporal resolution. Direct observations of CBZ vertical structure have been limited to only a few vertically-pointing Doppler radars and lidars (e.g., Martner 1997; May 1999; Demoz *et al.* 2006), and aircraft measurements (Geerts *et al.* 2006; Miao and Geerts 2007; Sipprell and Geerts 2007). Thermodynamic and kinematic properties within CBZs have been probed at limited levels with aircraft and surface instrumentation (e.g., Hane *et al.* 2002).

2. Data analysis and methodology

Primary data used to determine atmospheric thermodynamic and kinematic structure were obtained by MIPS (Karan and Knupp 2006). More details about CBZs in general and specifically the mature GF investigated in this study can be found in the dissertation by Karan (2007). Common meteorological variables at surface were sampled with 1 Hz temporal resolution. A 12-channel Microwave Profiler Radiometer (MPR) was used to derive vertical profiles of temperature (T) and water vapour mixing ratio (r_v), with 4 min temporal resolution. Vertical velocities and horizontal wind field (temporal resolutions of 1 and 1.5 min, respectively) were acquired by the 915 MHz profiler. Other data and observational platforms utilized in this study include a lidar ceilometer (Vaisala CT-25k), Hytop, AL Weather Surveillance Radar 88 Doppler

(WSR-88D) radar (KHTX) and Geostationary Operational Environmental Satellite (GOES) images.

2.1 Thermodynamic structure

Since both 915 MHz and MPR profilers make measurements at different vertical heights, and each instrument has different spatial and temporal resolutions as well as height coverage, thermodynamic and kinematic variables are mapped to a common vertical grid. The new vertical grids then contain the following variables; T , r_v , potential temperature (θ), pressure (p), MPR-derived virtual temperature (T_v), MPR-derived virtual potential temperature (θ_v), and three components of the wind, u (east–west), v (north–south), w (vertical) acquired from the 915 MHz profiler (figure 1). After thermodynamic and kinematic variables are interpolated and defined at the new grid points, thermodynamic structure and stability parameters (s , static stability; N , Brunt–Vaisala frequency; Ri , gradient Richardson number), are computed within the ABL. Instantaneous and 15 min averaged θ_v profiles are used to compute profiles of Brunt–Vaisala frequency defined as:

$$N = \left[- \left(\frac{g}{\bar{\theta}_v} \right) \left(\frac{\partial \bar{\theta}_v}{\partial z} \right) \right]^{\frac{1}{2}}, \quad (1)$$

where $\bar{\theta}_v$ represents 15 min averages.

Figure 1. Vertical grid structures of the MPR and 915 MHz profiler and the combined grid.

2.2 Kinematic structure

The horizontal wind (V_h) and the associated u and v components derived from the 915 MHz profiler are used to examine the time-height variation of wind shear associated with the GF. Mean vertical velocities w (radial velocity along the vertical beam) for every 30 s sample at 60 s intervals are used to infer ABL eddy and the GF updrafts and downdrafts. Mean vertical velocities are also used to calculate parcel displacement to determine various stabilities (through s and Ri). The ceilometer and solar radiation measurements are utilized to determine cloud presence and cloud base height.

3. General description of the GF

The mesoscale convective system (MCS) investigated during the time period of 12–13 June 2004 dominated the regions of Midwest US, north-central US, and the states of Arkansas, Tennessee, and Kentucky. The storm system was associated with damaging winds and hail without significant tornadic activities (Storm Prediction Center of NOAA – <http://www.spc.noaa.gov/climo/reports/040613.rpts.html>). During the time period 1700 UTC on 12 June–0600 UTC on 13 June 2004, the MCS initiated lines of convective cells aligned in northeast–southwest direction in the TN-KY region without forming any significant convective cells in the northern parts of Mississippi, Alabama, and Georgia.

The GF, after being initiated by the MCS in southern Tennessee, propagated southward and intersected with horizontal convective rolls (HCRs) which were oriented south–southwest to north–northeast (figure 2). The HCRs are depicted as dashed lines that are nearly perpendicular to the outflow boundary. The HCR axes and GF are associated with 0–5 dBZ and 15–20 dBZ reflectivity values, respectively. The radar reflectivity factors clearly indicate that each HCR after being intersected by the GF initiates convection north of the GF (behind the GF) and that the newly generated lines of convective cells appear to align with the HCRs. The MIPS sampled the GF as it transformed into a mature stage of its life cycle more than 2 h after its formation.

A time series of isochrones of the GF from 2335 to 0021 UTC is shown in figure 3. The GF movement vector is from about 30°. The elapsed-time and distance between the last and the first isochrones (0021 and 2335 UTC) are about 46 min and 27 km, respectively. This translates to a 9.9 ms^{-1} GF propagation speed during the time period. The MIPS sampled the gust frontal passage

Figure 2. Reflectivity factor (Z) from KHTX radar at 0.5 km altitude on 12–13 June 2004 at (a) 2214, (b) 2250, (c) 2320, (d) 0021 UTC. Locations of the MIPS and the radar are depicted as a square and open circles. x–y axes are the east–west and north–south distances in kilometres from the radar.

at around 0017 UTC, 3.5 hr after the GF formed in the north.

4. Detailed description of the mature GF

4.1 Gust front morphology

The MIPS sampled thermodynamic and kinematic structures of the GF as the GF passed over. The GF passage or the CBZ is defined as a transition zone comprising the GF updraft, and a very short period of downdraft beneath and behind the GF. The 915 MHz profiler (figure 4a and b) depicts properties of the GF and other related features. The drawing (solid black line) is used to clarify the GF body structure. Even though, under fair weather conditions (free of large scatters such as

birds and insects), the amount of returned signal power is due to the Bragg or clear air scattering (Ecklund *et al.* 1999), because of the convergent nature of the CBZ that draws shafts, dusts, insects and other scatters into its boundary, the most significant enhancement in signal-to-noise ratio (SNR) occurred within the CBZ below 0.4 km above ground level (AGL) ahead of the GF. The secondary high SNR region, after the CBZ passage, occupies a layer from the surface to 0.4–0.5 km AGL which roughly depicts the GF body. Turbulent mixing and large gradients in water vapour and temperature between the two distinct flows (outflow and the ambient air) enhance the refractive index gradient which yields large SNR gradients over the head and GF body. The height of the GF head (1.2 km, shown with an arrow) is 3 times higher than the GF depth of 0.4 km. Thus, the GF is composed of an elevated forward protrusion of

Figure 3. Time series of radar fineline acquired from KHTX at 0.5 km AGL on 12–13 June 2004. The open circle depicts the location of the MIPS and the vector displays the boundary movement vector. The background reflectivity field is valid at 2335 UTC. The reflectivity factors exceeding 10 dBZ are shown in black colour.

a nose, and a turbulent mixing region at the top behind the head. Local maximum vertical velocities ($1.0 \leq w \leq 3.5 \text{ ms}^{-1}$) associated with the GF are present from above the nose level to the top of the head (depicted as red dots at the top of the figure 4a). The figure also indicates that clouds were deepening as the GF passed over the MIPS.

As shown in figure 4(b), the GF comprises a major updraft and a downdraft with magnitudes of $3\text{--}4 \text{ ms}^{-1}$ and -2.5 ms^{-1} , respectively. The vertical velocities associated with the updraft are elevated above a weak stable layer which is confined to the lowest 0.5 km AGL. A discussion about the atmospheric stability is presented in section 4.5. A time series of w at 0.8 km from the beginning of the CBZ to the maximum downward velocity behind the GF is shown at the bottom of figure 4. This updraft–downdraft couplet can also be interpreted as an along-boundary component of the horizontal vorticity. A combination of the GF’s own circulation, horizontal vorticity generation within the GF head, and the absence of ambient vertical wind shear (section 4.3) caused these elevated updrafts to tilt back toward the gust frontal head. Figure 4(b) shows downward air motion beneath the updrafts within the CBZ. The downdrafts immediately follow the updrafts, and they even surge beneath the updraft region. Ceilometer backscatter (figure 4c) increased at and below the lowest

0.3 km altitude during the GF passage. The time of the maximum lidar backscatter and the downdrafts within the CBZ coincided, implying the presence of aerosol particles. Another region of strong backscatter occurred at the Lifting Condensation Level (LCL $\sim 1.4 \text{ km}$) where the lidar signals are attenuated by the cloud droplets. The cloud base height inferred from the returned power (figure 4a) and the maximum enhancement in lidar returned power are in agreement with each other.

The measurements of surface pressure, T_v , humidity, and wind taken at 4 m AGL were sampled at 1 Hz resolution and are shown in figure 4(d). Wakimoto (1982) outlined the sequence of meteorological events that accompanied GFs: a rise in pressure, a change in the wind direction, a sudden increase in the wind speed, a drop in the temperature, and precipitation (if any). The surface pressure (green) increased steadily during the CBZ passage while T_v (red) decreased sharply by 3.5 K. Almost all observed GFs exhibited a pressure increase prior to the arrival of the surface wind shift and cold air (e.g., Karan 2007). The dynamic pressure increase is concurrent with a minimum in surface wind speed and increased in low-level convergence, as inferred from the 915 MHz vertical velocity field and radar fineline signatures. The pressure increase begins 10 min prior to the GF. A weak periodic oscillation in pressure following the GF passage is noted and is correlated with the vertical motion above 1.5 km AGL (figure 4b). This low periodic oscillation in surface pressure, wind speed and direction behind the GF is thought to be a manifestation of the Kelvin–Helmholtz (K–H) instability that frequently occurs at the sheared interface between two air masses with different densities (e.g., Drogemeier and Wilhelmson 1987).

4.2 Thermodynamic structure of the GF

A detailed description of the MPR can be found in Karan (2007) and Karan and Knupp (2006). The following measurements can be provided by the MPR: temperature, mixing ratio, liquid water, integrated water vapour and cloud water. According to Solheim *et al.* (1998), Schroeder (1990), and Guldner and Spankuch (2001), the accuracy of microwave radiometer-retrieved temperature is about 0.6–1.6 K from low to higher altitudes and the accuracy of retrieved water vapour is around 0.2 gm^{-3} at low altitudes and 1.0 gm^{-3} at higher altitudes. Figure 5 indicates that the ambient average θ_v below the sub-cloud layer was about 310 K. The maximum r_v of 15 g kg^{-1} is located below 0.5 km AGL, and decreases slowly with height above this level. The thermodynamic boundary of

Figure 4. Time series of (a) SNR, (b) w , (c) two-way attenuation backscattering, and (d) surface observations on 13 June 2004. The cloud base heights (black dots) in (a) are derived from the ceilometer data. Additionally, relative maximum vertical velocities associated with gust frontal updrafts are shown with red dots, and the gust frontal body and its head are depicted with a drawing. A solid black line shown at 800 m AGL in (b) is used to investigate outflow-related circulation around the head of the GF which is pointed out with an arrow in (a). Pressure, wind speed and direction, and virtual temperature are shown in green, black, blue and red, respectively in (d). Time variation of the vertical velocity along the 800 m line is shown at the bottom.

the cold outflow near the GF is marked with a 309 K contour extending up to 1.4–1.5 km AGL, which roughly corresponds to the height of the GF head discussed earlier. The coldest air associated with 304 K within the cold dome occurs near the surface. Thus, the boundary passage was associated with a 6 K reduction in θ_v and a 2 g kg^{-1} increase in r_v . This change is relatively high when compared to dryline and sea-breeze frontal passages, which are usually less than 1–2 K. The r_v within the gust frontal updrafts and head structure shows significant increase at around 0020 UTC. This implies that the ambient air is lifted by the GF updrafts to higher altitudes within the CBZ. This process lowers the LCL, and potentially enhances the cloud depth, which is suggested by the high ceilometer backscatter and SNR values from 1.5

to 3 km AGL (figure 4). Across the boundary, the integrated water vapour increases by 10% from 5.0 to 5.5 cm, while absence of integrated liquid water before the boundary increases above 3 mm (figure 6a). Vertical profiles of cloud liquid water for some selected times during and right after the GF passage (figure 6b) indicate sharp gradients of cloud liquid water increase occurring at around 1.4 km altitude. The beginning of this pronounced enhancement suggests where the cloud base is, which can be confirmed by the ceilometer data in figure 4(c). The figure 6(a) also shows cloud deepening as high cloud liquid water amount extends up to 6.5 km height. The SNR from the 915 MHz profiler (figure 4a) verifies this enhancement in cloud depth right after the GF passage. Since the outflow circulation (positive in our example) did not have a

Figure 5. Time-height section of virtual potential temperature in K (coloured solid contours) and water vapour mixing ratio in g kg^{-1} (dashed) on 13 June 2004 derived from the MPR.

Figure 6. (a) Time series of integrated liquid water (bars-the left scale), precipitable water vapour amount (dashed-right scale), and virtual temperature (solid) on 12–13 June 2004. (b) Cloud liquid water profiles at 17, 24, 31, and 38 min after the 00 UTC on 13 June 2004 from MPR.

counterpart ambient circulation (absence of ambient wind shear, discussed in section 4.3) and a weak stable layer existed at low altitudes, the elevated updrafts were not vertically erect, but rather they were tilted back towards the gust frontal body. The aftermath of the boundary passage was a small and short-lived convective initiation event.

A sounding about 7 min before the CBZ (figure 7a) indicates a well-mixed convective boundary layer (CBL) with a dry adiabatic lapse rate and a near 16 g kg^{-1} mixing ratio. At this time, the most-unstable convective available potential energy (CAPE) and convective inhibition (CIN) were 1600 and 12 J kg^{-1} , respectively. Weak southwesterly flow from surface to middle CBL, and weak, mostly westerly flow occupied the upper CBL. The last sounding just prior to the CBZ was sampled at 0017 UTC (figure 7b). The near-surface dew point and temperature values at 0010 and 0017 UTC soundings are almost identical, yet r_v (T) increased for $1\text{--}2 \text{ g kg}^{-1}$ (decreased for about $1\text{--}2^\circ\text{C}$) within the lowest 2 km (1.5 km) AGL. The 0017 UTC sounding indicates the largest increase in r_v of 2 g kg^{-1} below 0.5 km where the outflow of the GF had already reached the MIPS, which is indicated by northerly wind flow. Moreover, just above this northerly flow, the ambient flow is much stronger than it was before. The CIN becomes zero and the most unstable parcel CAPE increases to 1900 J kg^{-1} . The LCL reduces by 200 m. The post GF sounding (figure 7c) shows that the outflow has the same direction as the movement vector of the GF (figure 3). The lowest 1 km AGL experiences the largest temperature decrease. Above the strong northeasterly outflow, the winds are variable in direction and speed. This layer corresponds to the cloud layer suggested by the local maximum SNR values between 1.5 and 3 km AGL in the top panel of figure 4.

4.3 Kinematic structure of the GF

The kinematic structure of the GF is determined by combining 915 MHz horizontal winds (V_h), 15 min resolution Doppler sodar, V_h , and surface observations (figure 8). Prior to the GF arrival, the wind speed decreased from the surface to the 0.5 km AGL. Therefore, the beginning of the CBZ is marked with a relative minimum in low-level wind speed, wind shift, and strong GF updrafts depicted in red dots. Following the GF passage, south-southwesterly 1 ms^{-1} surface wind increased to a 5 ms^{-1} northeasterly flow. Finally, the back of the CBZ is marked with downdrafts (blue dots).

The 5 ms^{-1} southwesterly ambient flow stayed nearly unidirectional within the lowest 2 km AGL. The GF passage occurred at around 0017 UTC

Figure 7. Thermodynamic soundings at (a) 0010 UTC, before, (b) 0017 UTC, during, and (c) 0024 UTC, after the gust frontal passage on 13 June 2004. The parcel trace is based on the most unstable level.

when the wind direction shifted to north–north easterly below 0.5 km. The northeasterly winds within the outflow increased to $8\text{--}11\text{ ms}^{-1}$ by 0025 UTC. A significant increase in wind speed of the ambient flow was also observed just above a turbulent mixing region above the GF body. The flow above 0.75 km, behind the local maxima in vertical velocities (behind the gust frontal head seen in figure 4) is 5 ms^{-1} greater than the pre-GF values at these altitudes. The highest horizontal winds within the GF body, wind gusts, occupied the 150–450 m layer.

As shown earlier in figure 3, the GF boundary was oriented from 300° to 120° . The direction of the ambient horizontal wind and the outflow (figure 8) are nearly perpendicular to the boundary, i.e., the ambient flow and cold outflow are opposite in direction.

Additional kinematical features can be deduced by rotating the coordinate system by 30° clockwise from north such that the x -axis becomes perpendicular to the GF. The time series observations are then converted to space assuming a frozen wind field over a 32 min period with a gust frontal propagation speed of 9 ms^{-1} . The resultant horizontal wind field consists of cross-boundary and along-boundary components. A time *vs.* height section of the cross-boundary flow is shown in figure 9 between 0012 and 0044 UTC. With this

new coordinate system, the boundary is located at $x = 0\text{ km}$.

The relatively weak ambient flow in advance of the GF opposed the direction of the outflow, which was confined below 350–400 m AGL. The updraft commences above 0.5 km AGL and the u - w wind field is tilted back toward the GF above. A rotor-like quasi-symmetrical circulation is centered near $x = 1.2\text{ km}$, over the head of the GF (also see figure 4a). The return (left to right) flow above and behind the head ($10\text{--}12\text{ ms}^{-1}$) is enhanced when compared to the flow in advance of the GF ($3\text{--}5\text{ ms}^{-1}$). This acceleration is shown to be a response of Bernoulli pressure buildup along the interface and geometrical shape of the front (e.g., Xu 1992). The wind speed of the low-level outflow is significantly reduced at the interval $5\text{ km} < x < 10\text{ km}$. The following argument can explain such reduction in wind speed—turbulent flow at the interface zone (0.5–0.75 km layer) could easily penetrate into this shallow gust frontal body causing disturbances within the outflow region.

4.4 Propagation speed

Using the isochrone analysis (section 3), the observed propagation speed of the gust front (V_{GF})

Figure 8. Time–height section of the horizontal wind field on 12–13 June 2004. The 5 min average winds derived from the 915 MHz profiler are shown in black. Winds in green are acquired from the Doppler sodar. Surface 5-min average winds (at 10 m AGL) and surface winds for every 30 s are shown in red and blue colours, respectively. Additionally, local maximum and minimum vertical velocities are depicted in red and blue dots, respectively. Full and half barbs represent winds less than 5.5 ms^{-1} and 3 ms^{-1} , respectively.

Figure 9. Cross-boundary-vertical velocity ($u-w$) component of the wind on 13 June 2004. The boundary is at $x = 0.0$ km in space or 0019 UTC in time domain.

was shown to be about 9.9 ms^{-1} . Time-averaged (~ 3 min), cross-boundary ambient flow ($\bar{U}_{\text{amb}}$) at 0009 UTC (figure 8) was averaged over the height of the outflow, and found to be about 3.6 ms^{-1} . The depth of the GF body suggested by the 915 MHz SNR and wind field (figures 4a, 8 and 9) was about 400 m. Simpson and Britter (1980) derived an equation to compute the propagation speed of the density current moving into an environment that has an ambient wind.

$$U = F_r \sqrt{\frac{\Delta p}{\rho_0}} + 0.62 \bar{u}_{\text{amb}}, \quad (2)$$

where U is the propagation speed, and ρ_0 is the density of the ambient air. The value of $\bar{u}_{\text{amb}}$ is an average quantity taken over the depth of the GF in the direction of the GF motion. The variation in surface pressure, Δp , is taken right during the GF head passage. Kingsmill and Crook (2003) employed equation (2) with a minor change. They used a value of 1.0 instead of 0.62 to account for the environment wind perpendicular to the boundary;

$$F_r = \frac{V_{\text{GF}} - (b) U_{\text{amb}}}{\sqrt{g'h}}, \quad (3)$$

and

$$g' = g \left(\frac{\bar{\theta}_{v-w} - \bar{\theta}_{v-c}}{\bar{\theta}_{v-c}} \right),$$

where g' is the reduced gravity, and $\bar{\theta}_{v-w}$ and $\bar{\theta}_{v-c}$ are averaged values for the ambient and the outflow. In this study, g' is computed using the average θ_v of the ambient and cold outflow over the depth of the GF body, and found to be about 309.5 and 306.6 K, respectively. The contours in figure 5 also

show that the coldest air (less than 307 K) was confined below 0.5 km AGL. Employing equation (3) with the above values yields Fr of 0.9 which is within the range found in most studies, and suggests that the GF in our example is dynamically similar to the gravity currents of laboratory simulations. Applying the surface values of virtual temperature change to the same equation results in an Fr value of 0.8, which is close to the previously calculated value. The fact that the GF observed in this study was shallow could be the reason for this close agreement.

Calculation of Fr was also performed using equation (3) with $b = 1$. The hydrostatic pressure increase across the GF boundary as seen in figure 4(d) is about 0.5 mb. The average density of the ambient air over the depth of the GF body, ρ_0 , was about 1.09 kgm^{-3} . Using these values and employing equation (1) results in an Fr of 0.8, identical to the value calculated using surface virtual temperatures.

The boundary propagation speed is proportional to the density difference between the environment and outflow as described by Simpson (1997) in the following equation:

$$U = \sqrt{\frac{2g\Delta\rho}{\rho_0}} h. \quad (4)$$

If some constant θ'_v profile is used within the outflow depth (i.e., the air density is constant within the outflow), then a faster propagation speed would be expected. Virtual temperatures of the ambient and cold outflow observed at the surface (305.5 and 302 K, respectively) are used to compute the ambient and outflow densities which are found to be

1.132 and 1.145 kg m⁻³, respectively. These values, along with outflow depth of 400 m produce a 9.7 ms⁻¹ propagation speed, which is close to the observed boundary speed (9.9 ms⁻¹). If the outflow depth of the GF is significantly shallow, as in this case, the difference in horizontal vorticity generated near the surface and near the top of the body would be small. Droegemeier and Wilhelmson (1987) used three different virtual potential temperature deficit profiles (step, linear, and cos² profiles) for GF simulations. They found that the outflow with linear temperature profile (like in this study) had faster speed than the step function outflow. The authors argued that the baroclinic generation of horizontal vorticity near the surface was largest in the linear profile simulation. Therefore, outflow at the leading edge of the boundary was the fastest. But, in their simulations, the depth of the GF body was 2 km, five times larger than in this case, and this yielded a significant difference in the magnitude of the horizontal vorticities near the surface and at the top. Their figure 7(b and c), in terms of the shape of the GF and vertical velocity field, closely resembles the observed GF of this study (figure 4).

4.5 Effects of stability and vertical wind shear on gust frontal circulation

In this section, the importance of thermodynamic and kinematic features of the ABL and their impacts on updrafts associated with the GF are examined. The squall-line strength and longevity is most sensitive to the strength of the component of low-level ambient vertical wind shear perpendicular to squall-line orientation (Rotunno *et al.* 1988; Weisman *et al.* 1988; Weisman and Klemp 1982; Weisman and Rotunno 2004). Although squall-lines are not the focus of this study, interaction of the low-level ambient flow with density currents is relevant. It is hypothesized that interaction between the low-level ambient vertical wind shear and outflow, together with the stability of the ABL, control the GF updraft characteristics.

4.5.1 Mathematical treatment

Rotunno *et al.* (1988) developed an idea that without wind shear, a spreading outflow creates a circulation within the gust frontal head. This circulation inhibits deep updraft development. This scenario typically portrays a classic density current, where the ambient air is lifted over a head region, and then subsides behind it. Rotunno *et al.* (1988) theoretically investigated gust frontal propagation speed and possible convective initiation by

utilizing the buoyancy term associated with the cold outflow and horizontal vorticity term. Herein the study adopts their approach and makes some modifications. If the flow is quasi-two-dimensional in the x - z plane at 1 h or less time scale, and the Coriolis force is negligible, then the horizontal vorticity component (η) directed along a hypothetical boundary becomes

$$\frac{d}{dt}\eta = -\frac{\partial B}{\partial x}, \quad (5)$$

where

$$\eta \equiv \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \quad (6)$$

is the horizontal vorticity in the along-boundary direction, B is the buoyancy, and u and w are the cross-boundary and vertical velocities, respectively. The buoyancy term is defined as (Houze 1993)

$$B \approx g \left[\frac{\theta'_v}{\theta_{v0}} + (\kappa - 1) \frac{p'}{p_0} - q_H \right]. \quad (7)$$

Equation (5) can also be written as:

$$\frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x}(u\eta) - \frac{\partial}{\partial z}(w\eta) - \frac{\partial B}{\partial x}. \quad (8)$$

Consider the GF in figure 10 moving with the edge of the cold air outflow. Integration of equation (5) from a point on the left, $x = L$, to a point on the right, $x = R$, of the cold-air edge, and from the ground to a level, $z = d$, yields

$$\begin{aligned} \frac{\partial}{\partial t} \int_L^R \int_0^d \eta dz dx &= \int_0^d (u\eta)_L dz - \int_0^d (u\eta)_R dz \\ &\quad - \int_L^R (w\eta)_d dx + \int_0^d (B_L - B_R) dz. \end{aligned} \quad (9)$$

If the flow is assumed to be steady state ($\partial/\partial t = 0$), the buoyancy of the ambient air is insignificant

Figure 10. An outflow in x - z plane is propagating into a no-shear environment. The letter h is the height of the outflow. The letters, L and R are far-point locations ahead and behind the outflow.

($B_R = 0$), and a region removed from the cold edge, the horizontal vorticity approximated by $\partial u / \partial z$ term, equation (9) becomes

$$0 = \left(\frac{u_{L,d}^2}{2} - \frac{u_{L,0}^2}{2} \right) - \left(\frac{u_{R,d}^2}{2} - \frac{u_{R,0}^2}{2} \right) - \int_L^R (w\eta)_d dx + \int_0^d B_L dz. \quad (10)$$

If the outflow is stagnant ($u_{L,0} = 0$), and restricted to a height $z = h$, equation (10) becomes

$$0 = \frac{u_{L,d}^2}{2} - \left(\frac{u_{R,d}^2}{2} - \frac{u_{R,0}^2}{2} \right) - \int_L^R (w\eta)_d dx + \int_0^h B_L dz. \quad (11)$$

If there is no shear at $z = R$ and a rigid plate at $z = d$, the second and the third terms of equation (11) vanish, and the equation becomes

$$u_{L,d}^2 = 2 \int_0^h (-B_L) dz \equiv c^2. \quad (12)$$

4.5.2 Application to the mature GF

Equations (5)–(12) are used in the following analysis. Since the atmosphere was free of hydrometeors, the last term in equation (7) vanishes. Also the contribution from the pressure perturbation term is neglected, since this term is only important within deep cumulus clouds. Buoyancy is determined using the relation

$$B = g \frac{\Delta\theta_v}{\theta_{v0}}. \quad (13)$$

The base state virtual potential temperature (θ_{v0}) profile is computed using ten MPR soundings within 1 h prior to the arrival of the GF. The profile of $\Delta\theta_v$ is computed using a representative thermodynamic sounding behind the outflow and the θ_{v0} base profile. Integration of the buoyancy term from near the surface to the top of the outflow boundary (using equations 12 and 13) yields

$$u_{L,d}^2 = -2 \sum_{i=0}^{i=N} g \frac{\Delta\theta_{v,i}}{\theta_{v0}} \Delta z \equiv c^2. \quad (14)$$

Figure 11. (a) 10 min averaged vertical variation of the cross-boundary component of the wind, valid at 0014 UTC and vertical variation of Ri number prior to the boundary passage, (b) time-height section of the 915 MHz measured Doppler velocities (vertical velocities), (c) vertical variations of the cross-boundary component of the wind within the outflow, and (d) Brunt–Vaisala frequencies before, during and behind the GF.

N and Δz are the number of grids within the outflow and the grid spacing, respectively. The above treatment applied to the observed GF passage in this study yields a propagation speed of 9.8 ms^{-1} , which is nearly same as the observed (9.9 ms^{-1}) propagation speed of the GF.

Large SNR values around the head structure, and gust frontal updrafts during the CBZ passage (figure 4a and b) indicate that the gust frontal circulation was the dominant circulation. The outflow generated positive (clockwise) circulation around the gust frontal head, yet, because of the weak low-level shear of the environmental winds, the ambient air was lifted at and around the head circulation. This circulation is indicated by the vertical velocity change with time at the 800 m level in figure 4. A maximum downdraft of 3 ms^{-1} was observed within 2 min after the maximum observed vertical velocity (4 ms^{-1}). The time period of about 11.5 min between 0017 and 0029 UTC represents an approximate 6 km distance in the x direction (see figure 9). Horizontal vorticity around the head circulation is controlled by the vertical shear ($\partial u/\partial z$) and the $(\partial w/\partial x)$ term. The latter term with the given maximum updraft and downdraft magnitudes measured by the 915 MHz profiler, and spatial distance in x direction (figure 9) is estimated to be $1 \times 10^{-3} \text{ s}^{-1}$. This term produces a positive horizontal vorticity. Figure 11(a) shows 10 min averaged vertical wind shear of the cross-boundary wind component, u , and dynamic stability of the ambient air. Figure 11(c) displays vertical shear, u , just behind the outflow from two consecutive samples at 1 min apart. The term $\partial u/\partial z$ is positive near the top of the GF ($\sim 0.5 \text{ km}$). The westward (negative) flow of 10 ms^{-1} shifts an eastward (positive) flow of 4.8 ms^{-1} within a 250 m depth just across the body at the edge of the outflow at 00:19:27. The vertical shear, therefore, is $59 \times 10^{-3} \text{ s}^{-1}$, which is about 60 times greater than the second term ($\partial w/\partial x$) computed above. Thus, the main controlling factor for the head circulation is the strong vertical shear generation across the top of the outflow body. Even though the ambient flow ahead of the GF has no vertical shear, since it was nearly perpendicular to the gust frontal boundary, it contributed about 30% of the vertical shear generation.

One of the most notable features of the GF investigated here was the elevated GF updrafts (figure 4b). The w values are plotted in figure 11(b). At 0018 UTC, the cold outflow below 0.5 km moved beneath the updraft region. Substantial positive vertical velocities existed only above 0.5 km AGL during this time. Vertical variations of the Richardson number are calculated at 0011 UTC prior to the CBZ passage. The lowest 0.25 km atmospheric layer was strongly stable with very high positive

values. Moreover, the whole layer from near the surface to 0.5 km AGL with few exceptions was stable. Negative values of Ri appear above 0.5 km, which suggests that the atmosphere is absolutely unstable above 0.5 km. The updrafts of the GF commenced where the unstable layer was present. Figure 11(d) shows profiles of the Brunt–Vaisala frequency (N^2) before, during, and after the GF passage. Prior to the GF arrival the ABL below 0.2 km AGL was statically stable as shown with positive values of N^2 . During the GF passage, stability of the ABL decreased in this layer, and became unstable between 0.5 and 1 km AGL. As the figure 11(d) suggests, some degree of instability between the 0.5 and 0.7 km layer prior to the GF passage is strengthened and expanded by the influence of the updrafts and downdrafts during the GF passage. Prior to the GF, statically strong stable layer below 0.2 km becomes less stable during the GF passage. The updrafts of the GF disturb the environmental air at 0.5 km altitude generating more instability while downdrafts could bring less cold and dense air down to the surface. This mixing results in less stable layer at the lowest altitudes at 0017 UTC. The lowest layer becomes more stable than before once the influence of the updraft–downdraft couple passes over the observing site.

The profile behind the GF indicates that the GF even more stable at the lowest 0.5 km AGL.

5. Conclusion

The MIPS' high temporal and spatial observations of a late-mature GF made it possible to document the detailed descriptions of GF characteristics; providing fine resolution of changes in thermodynamic and kinematic variables, updraft–downdraft couple associated with the GF passage, and overall gust frontal structure. The CBZ was shown to be a region comprising gust frontal updrafts and downdrafts. Backscatter intensity of the 915 MHz profiler clearly delineated the gust frontal head and body structure which were composed of an elevated forward protrusion of a nose, and a turbulent mixing region at the top and behind the head. The turbulent mixing zone atop the GF body coincided with local SNR enhancement and oscillations in virtual potential temperature. This is due to the mixing between the ambient air above and outflow air beneath. The beginning of the CBZ was marked with minimum wind speed, wind directional change and maximum GF updrafts.

The investigation on gust frontal updraft characteristics indicated that the updrafts were mainly

influenced by the adjacent ABL stability, and interaction of the ambient wind shear with GF circulation. The direct measurements of vertical velocities as the GF passed over the MIPS indicated that the updrafts were not surface rooted, but instead commenced at some certain altitudes. The Brunt–Vaisala and Richardson parameters computed using both the MPR and the 915 MHz profiler measurements have shown that the near-surface atmospheric layer ahead of the GF was strongly stable which inhibited vertical displacement of air parcels leading updrafts to commence just above this strongly stable layer. Because of the uniform, weak ambient flow, and insignificant ambient vertical wind shear, the horizontal vorticity generated solely by the GF caused updrafts to tilt back toward the GF head.

The GF passage was associated with a 0.6 mb non-hydrostatic pressure increase which coincided with a minimum wind speed. Time series of pressure perturbations at different altitudes (not shown) confirmed that the largest values of non-hydrostatic pressure increase occurred between near surface and altitudes equal to the depth of the GF. This increase in pressure took place about 10 min prior to the cold air of the GF. The horizontal wind speeds at these altitudes were also shown to attain their minimum values. The down-drafts within the head region marked the back of the CBZ.

The GF passage was associated with a 6 K reduction in θ_v and a 2 g kg^{-1} enhancement in r_v . These thermodynamic variations are significantly higher than those associated with passages of dryline and sea breeze fronts. The GF passage was also associated with reduced LCL due to the lifting of the ambient air within the CBZ by the GF updrafts to higher altitudes. This fact was indicated by the profiles of the mixing ratio across the boundary. The ceilometers, during the passage, indicated lowering cloud base height, meanwhile the 915 MHz profiler suggested vertical cloud development. This resulted in increased integrated liquid water from zero to 3 mm. There was only a very weak convective cell in close proximity to the MIPS that formed and died out quickly. After the coordinate rotation, the updrafts were shown to present above 350–400 m AGL and the cross-boundary ($u-w$) flow component was tilted back toward the GF above. The flow circulation around the GF head did not provide much of a lifting, rather, once the air parcels initially were lifted by the GF updrafts, they were immediately dragged back toward the GF body behind the GF head. This flow setting is not favourable for convection initiation. Soon after the GF passed over the MIPS, the radar observation indicated a small, short-lasting convection.

The GF propagation speed, computed via integrating the buoyancy term within the depth of the outflow, agreed well with the observed propagation speed of the GF through the isochrone analysis. The outflow generated a positive (clockwise) circulation around the GF head. The $\partial u / \partial z$ term within the CBZ was 60 times greater than the $\partial w / \partial x$ term. Therefore, the major contribution to the outflow circulation came from the vertical wind shear across the top of the outflow body. The dynamical similarity tests resulted in Froude numbers between 0.8 and 0.9 which confirm that the late-mature GF was dynamically similar to the laboratory simulated density currents.

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