Airborne Pseudo–Dual Doppler Analysis of a Dryline–Outflow Boundary Intersection

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ABSTRACT

On 3 June 1995, as part of the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX), the Electra Doppler Radar (ELDORA) onboard the National Center for Atmospheric Research (NCAR) Electra aircraft made possible a high-resolution examination of clear-air motions in the Texas panhandle in and around the intersection of the dryline and a surface baroclinic boundary, a location commonly referred to as the “triple point.” The ELDORA observations, as well as conclusions drawn from analyses of these data, are presented and discussed.

A transverse secondary circulation associated with the dryline is visualized through analyses of the ELDORA data. Typical values of rising and sinking air are found to be 2 m s\(^{-1}\) and 2–3 m s\(^{-1}\), respectively. These vertical velocities are approximately the same as those indicated by in situ data collected onboard the Electra. Because the maximum in rising motion is found at the western edge of the dewpoint gradient and because the low-level relative airflow was from the west, it is suggested that the source region for ascending updraft parcels was primarily from the dry side. The existence of a tilted circulation is also confirmed by dryline-normal cross sections of horizontal divergence, which exhibited a shift of the dryline convergence maximum to the east with height.

Based on vertical cross sections of analyses of ELDORA data just to the north of the triple point, it is shown that there is a residual dryline secondary circulation (RDSC) elevated above the cold pool. Composite hodographs representative of either side of the RDSC identify a distinct difference in the wind profile. The possible roles of the RDSC and outflow boundary to convective initiation are also discussed.

1. Introduction

The role of surface boundaries in the initiation of convection has long been a focus of study in mesoscale meteorology (e.g., Byers and Braham 1948; Purdom 1976; Wilson and Schreiber 1986; Lee et al. 1991). Although boundaries often serve to organize vertical motion on the mesoscale, the mere presence of boundaries does not guarantee the development of deep convection. Determining when and if convection will develop presents a major challenge to forecasters, especially when the ambient convective environment is potentially very unstable. Hence, pattern recognition often assists in determining relatively favored areas for development. For example, the region where a dryline and baroclinic boundary intersect (hereon referred to as the “triple point”\(^{1}\)) is often considered a preferred region for convective initiation (e.g., Kessinger and Bluestein 1979; Berry and Bluestein 1982; Koch and McCarthy 1982; Bluestein and Parks 1983). The triple-point region is one with a localized maximum in surface convergence in the ambient flow. Furthermore, vertical circulations associated with frontogenesis have been posed to increase this convergence (Eliassen 1962; Berry 1981; Berry and Bluestein 1982). Owing to mass continuity, air is forced upward through the convective boundary layer (CBL). This vertical motion is occasionally sufficient to overcome convective inhibition (CIN) in the ambient environment (e.g., inhibition due to insufficient moisture in the parcel source region, a capping inversion, etc.), so that the level of free convection (LFC) is reached and storm growth ensues.

On 3 June 1995, as part of the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) (Rasmussen et al. 1994), various types of data were collected, in the region around a triple point, by instrumentation aboard an Electra aircraft operated by the National Center for Atmospheric Research (NCAR). A variety of Electra in situ measurements were available (e.g., air temperature, dewpoint temperature, horizontal and vertical wind velocity, etc.) (Research Aviation Facility 1994a,b). In addition, the Electra Doppler Radar (ELDORA) (Hildebrand et al. 1994; Wakimoto et al.

\(^{1}\) Although the triple point is defined by the Glossary of Meteorology (Glickman 2000) as a tropical phenomenon, the term is also used colloquially to denote the intersection point of any three distinct air masses. The dryline–outflow boundary intersection and dryline–front intersection are examples of the triple point.
1996) sensed remotely scatterer reflectivity and velocity on both sides of the aircraft. The ELDORA collected data that afforded a finescale analysis of the individual boundaries that had set up over the Texas panhandle during the daylight hours of 3 June 1995, and provided clues as to how the boundaries interacted to allow for the development of deep convection.

Of particular interest in this study was the development and propagation of the dryline. The dryline (in the United States) is a boundary at the surface (often accompanied by confluence) that demarcates the western edge of the moisture moving upslope from the Gulf of Mexico against an arid, continental air mass originating from the elevated plateau over the southwestern United States and Mexico (Schaefer 1974). It is found most often in the central and southern Great Plains, where it is observed on about 40% of days during the spring months (Rhea 1966). In a large number of cases, drylines form in the warm sector of midlatitude cyclones, but they can form in the absence of any organized surface cyclone as well.

Since the dryline boundary is often marked by locally enhanced surface convergence, it has been widely identified as a location favorable for the initiation of deep convection. However, the issues related to the success or failure of convective initiation on a given day are not completely understood (e.g., Hane et al. 1993; Ziegler et al. 1995; Ziegler and Rasmussen 1998). Most often, deep convection well to the east of the dryline is precluded by a capping inversion above the CBL (e.g., Lanicci and Warner 1991). Even if this capping inversion has been eliminated, ascending parcels (particularly those with low specific humidity) may still be negatively buoyant above the former inversion level. Furthermore, even if there is positive buoyancy in this region, processes acting on the parcel (e.g., entrainment of dry environmental air) often preclude attainment of the LFC. To understand these processes better in the context of the dryline triple point, particularly its relation to the development of deep convection, it is necessary to investigate the thermodynamic and kinematic structure of the dryline.

Section 2 contains a brief description of the synoptic and mesoscale environment on 3 June 1995. In section 3 the methodology of the ELDORA analyses is explained. In section 4 results from the air mass ahead of the cold pool are presented. The ELDORA analysis of the triple-point region is shown in section 5, along with implications for convective initiation. A summary of findings is given in section 6.

2. Synoptic and mesoscale environment

A longwave trough at 500 hPa (Fig. 1) was well established over the southwestern portion of the United States during the first week of June 1995. Shortwave features embedded in this flow combined with surface convergence from processes related to the diurnal dryline cycle led to the development of numerous supercell thunderstorms over the period [e.g., VORTEX crews intercepted tornadoes on 2 and 8 June (e.g., Wakimoto et al. 1996; Markowski et al. 1998)].

The environment on 3 June 1995 was characterized by an east–west- and northwest–southeast-oriented baroclinic boundary (outflow boundary) generated from nocturnal (2 June) and early morning (3 June) convection over the eastern Oklahoma and northeastern Texas panhandles (Fig. 2). By 1815 UTC (all times henceforth given in UTC, subtract 5 h for local central daylight savings time), the leading edge of the outflow on 3 June was evident in visible satellite imagery as a narrow line of clouds separated from and just south of an area of enhanced cloudiness (Fig. 3). This east–west- and northwest–southeast-oriented boundary sagged slowly southward, becoming nearly stationary by midafternoon. In addition, a north–south-oriented dryline had developed and propagated eastward through the morning and early afternoon to a position just east of Lubbock, Texas. The dryline position can be identified in satellite imagery (Fig. 4) as the western edge of an area of cloud streets representing horizontal convective rolls (HCRs) in the boundary layer, the axes of which were aligned north–northwest to south–southeast, approximately along the mean boundary layer wind (to be shown later).

Deep convection was initiated over eastern New Mexico (near Tucumcari) at approximately 1900 UTC (Fig. 4). This activity was not related to the dryline, but instead was likely due to a combination of the aforementioned outflow boundary and a shortwave trough propagating into the area (Fig. 1).

Convective initiation near the triple point shortly before 2015 UTC (Fig. 5). The position of the convection relative to the outflow boundary and dryline can be seen in the reflectivity imagery from KLBB, the Lub-
bock, Texas, Weather Surveillance Radar-1988 Doppler (WSR-88D) (Crum et al. 1993) (Fig. 6). The convective cloud tops corresponding to the first period of convection were still evident at 2232 UTC (Fig. 7), approximately 2.5 h after that period of convection had begun at the triple point, as the dryline began to retrograde (retrogression began shortly after 2200 UTC). This first area moved off the triple point and was beginning to affect the Childress, Texas, vicinity [producing brief tornadoes just after 2300 UTC (NOAA 1995)]. Farther west, a second period of convective initiation was under way at the triple point, in the same location as the previous one. This activity also was responsible for some weak tornadoes as it approached the Childress area [at approximately 0315 UTC (USDC 1995)]. A third period of convective initiation after sunset, which produced another brief tornado near Quitaque, Texas, was evident in the KLBB reflectivity data (not shown).

3. Methodology for ELDORA data processing

The airborne Doppler radar data analyzed in this study came from the ELDORA. Recent studies have demonstrated the utility of this airborne platform in gathering useful clear-air data in the near-dryline environment (e.g., Wakimoto et al. 1996; Atkins et al. 1998). This platform permits both a high degree of spatial resolution and the ability to cover a large domain in a short amount of time.

The ELDORA was engineered to be used in conjunction with pseudo–dual Doppler analysis techniques (e.g., Hildebrand et al. 1996). To utilize these techniques, the ELDORA includes fore-looking and aft-looking antennas. One antenna is directed 18.5° forward of a plane normal to the aircraft flight track and the other 18.5° aft. As the aircraft moves, the use of two separate antennas allows each of the radars to sample a specific point in space from different viewing angles.
From these different angles, a wind vector field can be synthesized from the separate radial velocity measurements. The ability of the ELDORA to resolve clear-air motions in the CBL was fully demonstrated during VORTEX (Wakimoto et al. 1996). It has become generally accepted that passive tracers such as insects provide the primary source of scattering in clear air (Wilson et al. 1994).

The ELDORA operated in three scanning modes during VORTEX. The scanning parameters used for data collection in this study ("clear-air mode") are listed in Table 1. Even though the ELDORA had dual-pulse-repetition frequency (PRF) capability, a single 3-kHz PRF was used, owing to the anticipated smaller velocity scale of CBL motions (compared to that of deep convection). The antenna rotation rate was also slower than that in the convective mode, allowing for an increased dwell time inside the resolution volume, thereby yielding an increase in the number of independent samples that were averaged. The resulting enhanced sensitivity and accuracy of the ELDORA was necessary for CBL wind measurements, since motions on this scale are inherently turbulent and magnitudes of returned power are near the instrument’s noise level.

The raw ELDORA data were obtained via magnetic tape from the NCAR Atmospheric Technology Division (ATD). The data were then subjected to baseline corrections based on known systematic errors as reported.
FIG. 7. As in Fig. 2 but at 2232 UTC. Dryline indicated by scalloped line. The C denotes location of Childress, TX. Surface observations are from 2200 UTC.

in Lee et al. (1994) (e.g., aircraft roll, pitch, ground speed, etc.). From global positioning system (GPS) records of Electra position, the flight time was partitioned into 38 separate flight track “legs” in which nearly straight lines could be drawn between the beginning and end points. This technique was useful in limiting the domain analyzed at any one time, saving computational time while allowing better focus on a particular feature of interest (e.g., the outflow boundary or dryline or the location where they intersect). Electra data records also contained a wide variety of in situ meteorological observations, some of which were relied upon extensively throughout this research.

SOLO (Oye et al. 1995) software was employed for the purposes of perusing and editing the ELDORA data. This editing was necessary to remove areas of erroneous return (e.g., ground return, multitrip echoes). After the Doppler velocity and reflectivity data were edited, they were objectively analyzed by REORDER (Oye and Case 1992), which uses a Cressman objective analysis scheme (Cressman 1959), onto a Cartesian grid. Grid spacings of 600 and 100 m were chosen for the horizontal and vertical planes, respectively. The radius of influence for the inverse Cressman weighting scheme were 450 and 200 m in the horizontal and vertical, respectively. These values were deemed large enough to be on the order of the resolution of the data, which is just under 500 m in the along-flight direction and about 250 m in the vertical at the range of the targets (Table 1), but small enough to avoid excessive smoothing.

The gridded fore and aft Doppler velocity data were analyzed using NCAR/Mesoscale Microscale Meteorology (MMM) Custom Editing and Display of Reduced Information in Cartesian Space (CEDRIC) software, through which the horizontal wind field was synthesized using standard dual-Doppler principles (e.g., Miller and Strauch 1974). The synthesized horizontal wind field was filtered to reduce noise. As a result of aliasing, scales of motion shorter than ~1 km are not resolvable in Doppler velocity data owing to the relatively slow antenna rotation rate (see Table 1). A two-step Leise filter (Leise 1982) was imposed on the horizontal wind field, thus removing much of the energy of wavelengths shorter than 3.3 km, as had been done by Atkins et al. (1998). To obtain the vertical component of motion, the anelastic mass continuity equation was integrated upward from the surface using a lower boundary condition of $w = 0$ m s$^{-1}$.
4. ELDORA clear-air return analyses

a. Ambient environment and outflow boundary

The Electra utilized a box-survey scanning strategy on 3 June 1995, in which the aircraft flew at nearly constant altitude (∼400 m AGL) throughout the mission. These surveys permitted a detailed perspective into the horizontal mesoscale structure of the preconvector environment. The approximate ELDORA data domains of relevant flight legs used in this paper are shown in Fig. 6.

A nearly east–west-oriented reflectivity maximum associated with the outflow boundary was evident in the analyses of ELDORA data from leg 7–8 (2106–2112 UTC) (Fig. 8). Numerous inflections were noted along the length of this boundary to the west of the dryline, which could be identified by noting the position of strong cyclonic wind shear and curvature along the reflectivity maximum. To the east of the dryline the outflow boundary was not clearly indicated in the reflectivity or wind field. South of the outflow boundary, near × = 17 km, reflectivity increased locally to about 6 dBZ, as flight-level winds decreased to 5–10 m s⁻¹. It is hypothesized that this area coincided with the upward branch of circulations associated with one or more HCRs (Kuettner 1959) since the location of this feature agreed with that of finelines seen in the reflectivity data from the KLBB WSR-88D (Fig. 6).

b. The 3 June 1995 dryline

The first study of a dryline was done by Fujita (1958), who discussed the concept of a “dry front” and its role in associated thunderstorm development. The National Severe Storms Project staff members (NSSP 1963) furthered this seminal work by conducting a detailed observational study of the dryline. They found dewpoint gradients on the order of 18°C over distances of 1–10 km in the horizontal. Subsequent studies have focused on many issues related to the dryline including dryline motion (e.g., Sun and Wu 1992; Hane et al. 1993; Ziegler and Hane 1993), finescale structure and along-line variability (e.g., Parsons et al. 1991; Hane et al. 1993, 1997; Shaw et al. 1997; Atkins et al. 1998), surface characteristics of dryline passage (e.g., Schafer 1974; Koch and McCarthy 1982; McCarthy and Koch 1982; Sanders and Blanchard 1983; Crawford and Bluestein 1997), and convective initiation (e.g., Bluestein and Parker 1993; Ziegler et al. 1997; Ziegler and Rasmussen 1998).

The dryline for this case study exhibited many of the features noted in previous studies and observations. At 1200 UTC on 3 June, there was a sharp horizontal gradient in dewpoint over the southern portions of the Texas–New Mexico border (at least 10°C over 100 km, based solely on observations from the synoptic network) (Fig. 9a). Dewpoints were relatively high to the east of the dryline (e.g., just under 20°C in Lubbock).

Satellite imagery from the early morning showed shallow stratus associated with the moist air to the east of the dryline (not shown). The western edge eroded very quickly as strong mixing occurred during the late morning hours. As a result, the dryline propagated quickly eastward, and by late afternoon was located along a north–south line approximately 20 km to the east of Lubbock (Fig. 9b). At this time the dryline became nearly stationary. Geostationary Operational Environmental Satellite-8 (GOES-8) imagery from the evening of 3 June (Fig. 7) showed a narrow band of shallow cumulus convection extending along the length of the dryline.

ELDORA data from leg 7–8 were used to obtain the first airborne analysis of dryline features (Fig. 8), within a nearly north–south-aligned zone of confluence and relative maximum in flight-level reflectivity extending from the outflow boundary at grid location (27, 6) southward to near (28, −8) (the reflectivity maximum is not as apparent south of the flight track). ELDORA-measured winds to the east of the dryline were from the south-southeast at about 10 m s⁻¹. Just to the west of the dryline, in the fully mixed CBL, winds veered to the southwest at about 10 m s⁻¹, and decreased to 5–10 m s⁻¹ farther to the west.

c. Secondary circulation and dryline propagation

The time rate of change of dewpoint gradient across the dryline is often much greater than that explained solely by confluence of winds on the larger mesoscale (e.g., that on the scale of hundreds of kilometers) (e.g., Parsons et al. 1991). As a result, additional frontogenetical processes related to the dryline have been investigated as a cause of the locally intensified dewpoint gradient. Sun and Ogura (1979) suggested that the “inland sea breeze” is responsible for a vertical circulation in the plane normal to the dryline. The basis of their theory is that a solenoidal circulation is forced by changes in the virtual temperature (i.e., density) gradient across a boundary separating distinctive air masses (e.g., a “sea breeze” boundary separating a virtually warm continental air mass from a virtually cool marine air mass). The changing density gradient at the surface induces cross-frontal ageostrophic accelerations, a low-level inflow of cool, moist air. On the scale of the dryline

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**Table 1.** Parameters used for clear-air scanning in VORTEX-95 (from Wakimoto et al. 1996, their Table 1).

<table>
<thead>
<tr>
<th>Scanning parameter</th>
<th>Value used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna rotation rate (° s⁻¹)</td>
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</tr>
<tr>
<td>No. of samples per radar volume</td>
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</tr>
<tr>
<td>PRF (Hz)</td>
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</tr>
<tr>
<td>No. of range gates</td>
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<tr>
<td>Gate length (m)</td>
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<tr>
<td>Sweep-angle resolution (°)</td>
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</tr>
<tr>
<td>Along-track resolution (m)</td>
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</tr>
<tr>
<td>Maximum range (km)</td>
<td>50</td>
</tr>
<tr>
<td>Maximum unambiguous velocities (± m s⁻¹)</td>
<td>23.6</td>
</tr>
</tbody>
</table>

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Fig. 8. Plan view image of leg 7-8 at z = 400 m AGL, from 2106 to 2112 UTC on 3 Jun 1995. Horizontal winds (m s$^{-1}$) indicated by vectors; radar reflectivity factor (dBZ) indicated by shading (scales for both at bottom of figure). The x (y) axis points due east (north). The black box represents the averaging domain for the cross section shown in Fig. 10. The red arrow represents the direction of the Electra flight track, which approximately coincides with the data-free swath. The blue arrows along the track indicate in situ flight-level wind measurements.
convergence zone, there often exists a rotor circulation on the “head” of the inland sea breeze with downward motion ~10 km to the east of the upward motion (e.g., Atkins et al. 1998). Mass continuity requires ascent in the region of surface convergence (often observed as a fineline on radar) and return flow above inversion height. The cross-frontal acceleration at the surface increases confluent flow above that which previously existed, thereby further intensifying the virtual temperature gradient.

A secondary circulation associated with the 3 June 1995 dryline was evident in east–west cross sections of ELDORA data from leg 7–8 (Fig. 10). A number of individual cross sections in the cross-dryline direction were averaged to yield a better estimate of the dryline circulation under the assumption that variations in the north–south direction are of lesser importance. The cross-section domain included most of the area to the south of the outflow in leg 7–8 (ref. Fig. 8), along a 12-km length of the y axis. For a horizontal grid spacing of 600 m, Fig. 10 represents an average of 20 individual cross sections.

The upward branch of the secondary circulation (Fig. 10) was located near $x = 28$ km. Peak values of the averaged upward vertical velocity in this branch were about 2 m s$^{-1}$. Similarly, the averaged downward motion$^2$ in the subsiding branch of the circulation (near $x = 35$ km) peaked at approximately 2–3 m s$^{-1}$.

The magnitudes of upward motion at the dryline were consistent with those of some previous observational studies of the dryline [e.g., $w = 3$ m s$^{-1}$ from Sun (1987); $w = 5$ m s$^{-1}$ from Parsons et al. (1991); $w = 2–5$ m s$^{-1}$ from Ziegler et al. (1997); $w = 1–2$ m s$^{-1}$ from Ziegler and Rasmussen (1998)]. The Doppler radar–derived vertical velocities were supported by in situ data taken from the Electra aircraft as it was performing leg 7–8 (Fig. 11). It is noted that there was a decrease in dewpoint immediately to the east of the maximum value (at 2110:47 UTC), which is suggestive of an upward bulge in moisture in the eastern portion of the dryline zone,$^3$ as postulated in Ziegler and Hane (1993). The upward vertical velocity maximum of 3–4 m s$^{-1}$ occurred on the west (dry) side of the dewpoint gradient. This observation is also consistent with previous findings (e.g., Sun 1987; Hane et al. 1997; Sun and Wu 1992). Schaefer (1986) suggested that since heat and moisture mix more efficiently than momentum, a site on the surface experiencing dryline passage would realize turbulent mixing of moisture before winds veer, creating the observed displacement between the dewpoint maximum and the surface convergence (and upward vertical velocity) maximum. Owing to this displacement, it is suggested that the source region for the ascending parcels is primarily from the dry side. Further evidence is seen in Fig. 10 that the rising parcels in the secondary circulation originated primarily from the dry side.

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$^2$ Since the anelastic mass continuity equation is integrated upward to obtain $w$, the errors incurred from inaccuracies in the synthesized horizontal wind field and inadequate sampling increase with height as well. Although the results are likely correct qualitatively, the magnitude of motion in the upper portion of the domain probably has significant error.

$^3$ The exact location and magnitude of dewpoint maxima/minima must be interpreted with some degree of caution since the chilled-mirror sensors used have a lag in response time, and may have reacted slowly in the sharply changing environment of the dryline.
side since relatively little easterly flow was evident at the base of the convergence zone.4

Maximum values of dryline surface convergence ($\sim 2 \times 10^{-3} \text{ s}^{-1}$) were found in the lowest 1 km of the CBL (Fig. 12). These locations were east of an absolute maximum in the $u$ component of the wind. It is noted that the surface convergence maximum generally tilted to the east with height (at a slope of about 1:3).

While the upward branch of the circulation is most important for its association with convective initiation, the downward branch may be a critical factor in the propagation of the dryline. An intrusion of dry air aloft by the downward branch may enhance mixing to the east of the existing dryline position (Hane et al. 1993), thereby complementing sensible surface heating in mixing out the CBL and furthering dryline propagation. The cause for this type of intrusion has been linked to the production of turbulent kinetic energy associated with vertical shear instabilities across the boundary layer interface (Lenschow et al. 1980). Parsons et al. (1991) found periodic perturbations in pressure-gradient force (consistent with the existence of gravity waves) that explained these downward surges of dry air. Even with the large amount of downward motion evident in Fig. 10, the dryline had ceased eastward movement and remained nearly stationary by the time of this analysis. This lack of movement seemed rather contradictory; however, other factors may have mitigated the propagative effect of mixing.

One possible mitigating factor is the effect of soil moisture on retarding dryline propagation. Lanicci and Carlson (1983) suggested that horizontal gradients in soil moisture might explain enhanced easterly ageostrophic winds across the dryline. Recent work has further focused on the relation between land use and CBL properties (e.g., Basara and Crawford 2002). It is seen in a composite of visual surface greenness (Fig. 13) as derived from the Advanced Very High Resolution Radiometer (AVHRR) aboard a polar-orbiting National Oceanic and Atmospheric Administration (NOAA) satellite on 1 June 1995 that the percentage of active vegetative cover increased gradually to the east through the southern Texas panhandle, with a sharper gradient in greenness (i.e., the quick transition from light to dark shades in Fig. 13) running nearly perpendicular to the 3 June 1995 dryline orientation in the central Texas panhandle. To the east of the dryline, where greenness percentages are much higher, a larger amount of incoming solar radiation is partitioned to latent heat flux (Basara and Crawford 2002), thereby reducing the amount of surface sensible heat flux (which is required to increase CBL depth and, eventually, to mix the CBL with air above the inversion height). The vegetation gradient in Fig. 13 also ran perpendicular to the Caprock escarpment, a terrain feature that runs approximately north–south, about 40 km to the east of Lubbock. The rapid increase in CBL depth due to this nearly discontinuous elevation change across the escarpment requires a substantial increase in integrated sensible heating for complete mixing out of the CBL (dryline passage) to occur. Both of these arguments support the position of the dryline on the afternoon of 3 June. The proposed enhancement of the easterly ageostrophic wind component forced by the land use gradient may also explain the lack of eastward dryline advancement through the afternoon of 3 June, though measurements were not available to confirm this.

5. Issues related to the triple point

The ELDORA analyses provided valuable information on the triple point, since they documented some of the unique features of the environment in this region. Specifically, the answers to two major questions were sought: 1) do the individual environments on either side of the dryline maintain their uniqueness north of the outflow boundary (above the cold pool)? and 2) how do the individual boundaries contribute to the initiation of deep convection [i.e., what is (are) the mode(s) of storm development near the triple point?]?

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4 Since the dryline was nearly stationary, the ground-relative flow pictured in Fig. 10 is approximately identical to dryline-relative flow.
Figure 11. Dewpoint (black squares) and a running 9-s (~1 km) average of vertical velocity (gray diamonds) from in situ data collected onboard the Electra (2106–2112 UTC). Numbers along $T_d = 0^\circ C$ axis indicate seconds of the valid UTC time. Approximate time-to-space conversion scale indicated in lower-right corner.

**a. The residual dryline secondary circulation**

In exploring the nature of the triple point, it was useful to develop a conceptual model, termed the 3 1/2 quadrant model (Fig. 14). Certainly there is a substantial difference between the boundary layer environments on either side of the dryline, to the south of the outflow [typical temperature, dewpoint, and wind profiles might be like those shown in quadrants III and IV (e.g., Ziegler and Rasmussen 1998)]. To the east of the dryline, a moist boundary layer in which winds have an easterly component is capped by a thermal inversion. To the west, the CBL has mixed considerably with the environment above, resulting in winds with a westerly component and lower specific humidity. As there are thermodynamic and kinematic differences across the dryline, there are also obvious differences in characteristics across the outflow boundary, since cold, stable air spreads beneath the preexisting CBL. The question then is whether the two unique air masses south of the outflow maintain their individual properties as they are advected northward over the cold pool (i.e., are quadrants I and II indeed distinct above the cold air?).

The outflow depth as determined from an east–west ELDORA cross section through leg 11–12 (taken about 1.5 km to the north of the outflow boundary) is approximately 700–800 m (the depth of strong easterlies) (Figs. 15, 16a). Above this cold pool, near $x = -15$ km, there is a rotor circulation. The longitude of this circulation is approximately the same as that of the dryline ahead (south) of the outflow boundary (consider the eastern boundary of westerly momentum in Fig. 15). It is postulated that this rotor is a *residual dryline secondary circulation* (RDSC), since it represents the horizontal vortex tube associated with the active dryline secondary circulation advected up and over the cold pool (the use of the term residual will be explained below). The dryline circulation and the RDSC have the following features in common: updraft and downdraft positions remain consistent in the east–west direction; there is ascent (descent) at the longitude of the western (eastern) edge. Magnitudes of vertical velocity are of the same order as those found ahead (south) of the outflow, although absolute values are somewhat lower (~1

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This outflow depth is also supported by VORTEX mobile soundings taken behind the outflow boundary (not shown).
m s$^{-1}$. Furthermore, the distance between the respective extrema in vertical motion is about 5 km, comparable to that observed ahead (south) of the outflow (Fig. 10).

The existence of the RDSC prompts the question of whether this circulation was frontogenetical [a frontogenetical circulation is forced when a gradient in virtual potential temperature is superposed upon a confluent flow (Miller 1948)]. In the particular case of the dryline, frontogenetical processes are strongly tied to the surface. For example, Sun and Wu (1992) found that terrain slope and horizontal gradients in surface heating and soil moisture were critical for the maintenance of the virtual temperature gradient across the dryline. Are these processes still important for the RDSC? The RDSC was not directly influenced by the surface since it was isolated from the surface by outflow. However, there was likely still an indirect effect from the surface since near-surface air was being directly adveced up and to either side of the elevated dryline circulation. The intensity of this indirect forcing likely decayed with increasing distance from the outflow boundary, since mixing acted to modify these individual air masses. An
individual leg 11–12 cross section 3 km farther to the north of that in Fig. 16a supports this notion (Fig. 16b). In this cross section upward motion is again seen near $x = -15$ km. However, the complete rotor circulation is not as evident as seen closer to the outflow boundary (Fig. 16a). A cross section constructed from an average of 11 leg 11–12 individual cross sections (Fig. 16c) indicates clearly the presence of the RDSC.

Composite hodographs from quadrants I and II were created from ELDORA pseudo–dual Doppler wind analyses (e.g., Rabin et al. 1982). Data were taken from either side of the RDSC in leg 11–12 (see Fig. 15). Wind vectors at 40 grid points were averaged over the horizontal domain at each level in the vertical (refer to the red boxes in Fig. 15). There is a distinct difference in the shape of the composite hodographs above the cold pool (Fig. 17a). In quadrant I, winds exhibit a negative $u$ component (easterly) through a greater depth (1.3 km) than they do in quadrant II (0.9 km). These profiles indicate convergence throughout the boundary layer above the cold pool. The individual wind profiles on either side of the dryline extension were consistent with those to either side of the dryline (south of the outflow boundary) (Fig. 17b), in that there was a deeper
b. Convective initiation

To the east of the RDSC, between $x = -10$ km and $x = -5$ km, upward motion is present above the outflow layer (Fig. 16c). This area is correlated with an increase in the depth of higher reflectivity, as CBL scatterers are presumably more strongly concentrated in the convergent flow and carried upward. This region of vertical motion is associated with deep cumulus convection at and to the northeast of the triple point. The proximity of the developing towering cumuli to the RDSC (and the triple point in general) identifies the RDSC as a possible focus for the initiation of deep convection.

For convective initiation to occur, a parcel must attain both the lifted condensation level (LCL) and the level of free convection (LFC). Ziegler and Rasmussen (1998) found that moist CBL air parcels must attain both the LCL and LFC before leaving the updraft associated with the dryline secondary circulation. Even if conventional parameters [e.g., large convective available potential energy (CAPE), near-zero CIN] support the formation of deep convection (necessary) but not sufficient conditions), other factors need to be considered (e.g., the depth of mass convergence, the presence of elevated dry layers between the LCL and LFC that detrain the moisture in ascending parcels).

One must consider the possibility that the triple point had no special significance in convective initiation. In other words, either the outflow boundary or dryline might have initiated deep convection separately; that is, it was a coincidence that storms developed at the intersection point of the two boundaries. The longevity of convective initiation in the same location (three separate periods of initiation in $\sim 6$ h) is a strong indication that the triple point was indeed a preferred locale. Furthermore, no deep convection formed in Texas on either individual boundary away from the triple point (i.e., no “pure dryline” or “pure outflow” convective initiation).

To the east of the dryline, the atmosphere was characterized by a classic moist airmass sounding (e.g., Bluestein 1993) (Fig. 18). The LCL and LFC in this sounding are 1.4 and 2.7 km AGL, respectively. For a variety of reasons, each of the boundaries in the triple-point region was unable to initiate deep convection separately. HCRs, by their very nature, were confined to the CBL ($\sim 2$ km in this case) and, therefore, were incapable of bringing parcels to LFC height in this case. However, the LCL was achieved rather easily, as evidenced by the fields of cumulus clouds that formed along the HCR axes east of the dryline (Fig. 4). Likewise, the outflow boundary was too shallow (700 m) in its decaying stage to force parcels to the LFC even though the depth of influence was evidently somewhat greater than the physical depth of the cold pool. The larger depth of vertical motion above the outflow body is likely a result of the vertical nonhydrostatic pressure gradient force attributable to the stagnation point at the head of the density current (Benjamin 1968).

The reason for the lack of convective initiation along the dryline was not as obvious. Even though the vertical extent of the ELDORA data, which was limited by rapidly decreasing scatterer concentration with height, was inadequate to diagnose vertical motion above 2 km AGL, it appeared that the vertical motion associated with the upward branch of the secondary circulation might have been sufficient to achieve the LFC. However, the proximity sounding (Fig. 18) shows an elevated dry layer extending from above the capping inversion to the LFC. Therefore, as described by Ziegler and Rasmussen (1998), after parcels reached the LCL they may have detrained moisture while in this dry layer and were, therefore, unable to reach the LFC. In addition, as a result of the pronounced tilt of the secondary circulation (Fig. 12), it is suggested that the horizontal advection of dry air from the west retarded the vertical flux of moisture in the dryline updraft.

Even though the dryline, outflow, and HCRs were unable to bring air parcels to their LFC, it is suggested that the combination of these features may have been able to phase constructively so that the total upward vertical velocity was greater in magnitude than that associated with each alone. Stronger vertical velocity in-
increased the likelihood of lifting moist parcels to the LFC in spite of detrainment. The RDSC is an example of such constructive phasing (Fig. 19a). Looking once again at a cross section through the RDSC (Figs. 16a–c), vertical motion was evidently forced through the top of the domain (2 km) above the residual rotor. Since this rotor was displaced above the surface, owing to lift over the cold pool, air parcels experienced vertical mo-
tion to a greater height. If the LFC of 2.7 km (Fig. 18) was indeed representative, then it is quite likely that the RDSC could have initiated deep convection. As presented before (Figs. 16a,b), the RDSC shrunk in physical dimension with distance north of the outflow boundary (or, equivalently, time after crossing the outflow boundary). Therefore, the most favorable location for convective development was where the vertical motion was strongest and deepest—when the dryline circulation was first lifted (i.e., at the triple point).

As evident in satellite and reflectivity imagery, the outflow boundary was quite well established and con-
tributed significantly to the dynamics of the convective environment. The cold pool, however, may contribute more than a simple physical upward displacement of air parcels. A case study presented by Hane et al. (1997) revealed the importance of a convergent line oriented at a large angle to the dryline in explaining along-dryline variability (in particular, storm development). The origin of this convergence line was hypothesized to be due to differential land use properties. A local thermally direct circulation could develop as a result of differential sensible heating, owing to horizontal differences in vegetation and cultivation. Also, horizontal gradients in vertical mixing (perhaps related to the aforementioned gradients in land use) could create a localized deflection of surface winds, increasing convergence. Whatever the reason for the convergent line, the upward motion along its length forced air parcels to their LCL (as proven by the existence of cumuli along the line). However, no storm initiation took place along this line to the west of the dryline, where parcels had not achieved their LFC. Naturally, LFC heights (if they exist) are quite high to the west of the dryline, owing to the relatively low amount of surface moisture. Conversely, to the east of the dryline, LFC heights are lower as a result of the increased moisture. So, if the intensity of the vertical circulation forcing cumulus development remains relatively constant, then parcels may suddenly achieve LFC as they are advected across the dryline. In essence, the secondary line serves as a “primer” for later convective development by establishing the thermally direct circulation (Fig. 19b).

It is hypothesized from the 3 June case study that the mature outflow boundary may have assumed a nearly identical role to the secondary convergence line mentioned by Hane et al. (1997). Both boundaries had pronounced surface convergence and forced ascent. However, the major difference between the two was the existence of a cold pool behind the boundary in the current case. Therefore, the high-based cumuli that formed resided above this shallow cold pool (in quadrant II of the 3 1/2-quadrant idea). Instead of crossing the dryline per se, these circulations may have initiated deep convection as they crossed the dryline extension. This idea leads to the conclusion that the deep convection was elevated (increasingly so, farther north away from the gust front). It is likely that the slightly elevated nature of these storms delayed tornadic development (as observed) until updrafts were sufficiently strong to penetrate the shallow cold pool (i.e., with parcel trajectories coming directly from the surface). A satellite image (Fig. 20) includes the triple point area about 30 min prior to convective initiation. There were numerous cumulus clouds in quadrant II during this period, consistent with the above hypothesis.6

6 Another possible explanation for the cumulus in quadrant II is the intersection of dry-side HCRs with the outflow boundary.
A well-defined dryline was situated over the central Texas panhandle on this day; a dewpoint gradient of at least 10°C (100 km)⁻¹ was evident from the standard observing network. ELDORA analyses provided clear evidence of the transverse secondary circulation associated with the dryline. This circulation was broadly consistent with the principles of the “inland sea-breeze” hypothesis as posed by Sun and Ogura (1979), in which the virtual temperature gradient near the surface drives a solenoidal circulation. Typical averaged values of ascent and descent were found to be 2 and 2–3 m s⁻¹, respectively. These values are approximately the same as those indicated by in situ data collected on board the Electra. Since the maximum in rising motion is on the western edge of the dewpoint gradient, the source region for ascending updraft parcels was primarily on the dry side, a conclusion also supported by inferred trajectories in the dryline cross section. The notion of a tilted circulation was also confirmed by cross sections of averaged horizontal divergence, which showed the relative convergence maximum tilting to the east with height. Because downward vertical motion to the east of the dryline was so strong and coherent, there was an environment favorable for eastward dryline advancement with enhanced mixing across the inversion at the top of the CBL. However, both enhanced ageostrophic backing of the winds to the east of the dryline due to lee troughing (isallobaric forcing) and horizontal gradients in soil moisture likely played a role in halting dryline advancement during the afternoon hours (above that due to the diurnal decrease in incoming heat flux).

Analyses of cross sections of ELDORA data just to
the north of the triple point show a residual dryline secondary circulation (RDSC) elevated above the cold pool. The presence of this feature points to the possible existence of the individual air masses on either side of a “dryline extension.” Composite hodographs generated on either side of the extension support this notion of separate air masses. Individual cross-section analyses of the RDSC indicated that the physical dimensions of this circulation diminished with distance north of the outflow boundary.

The mode of convective initiation at the triple point was also investigated. One possibility involved the superposition of boundaries, in which the vertical motion experienced at the triple point was a combination of that owing to each of the individual boundaries comprising the triple point. The RDSC was a fine example, as the upward motion near the outflow boundary plus the dryline residual upward vertical velocity may have been sufficient to bring a moist parcel intact to the LFC. Another proposed mode of initiation involved the role of the outflow boundary as a “primer” for deep convection by allowing parcels to attain their LCL (but not their LFC) to the west of the dryline, similar to a convergent line positioned west of the dryline in Hane et al. (1997). As these circulations crossed the dryline extension into an air mass with an inherently lower LFC height, explosive convective initiation could have taken place.

We recognize the need for numerical simulations to understand better the sensitivity of the triple point (and associated convective initiation) to the many degrees of freedom in the near-dryline and near-outflow environments. Numerical simulations of this case study are in progress, the results of which will be discussed in a forthcoming paper.

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