Frontal and Radar Refractivity Analyses of the Dryline on 11 June 2002 during IHOP

ROGER M. WAKIMOTO
National Center for Atmospheric Research, Boulder, Colorado

HANNE V. MURPHEY
Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, California

(Manuscript received 4 March 2009, in final form 14 July 2009)

ABSTRACT
An analysis of a dryline that did not initiate convection during the observational period is presented. The dryline was the weakest kinematic boundary observed during the International H2O Project (IHOP), but was associated with a large moisture gradient. Detailed dual-Doppler wind syntheses from an airborne Doppler radar were combined with radar refractivity measurements providing a rare opportunity to examine both the kinematic and moisture characteristics of this boundary. The radar thin line denotes the approximate kinematic position of the dryline and was quasi-linear on this day. In contrast, the moisture pattern across the dryline was more complex than was suggested by the characteristics of the thin line. Prominent in the horizontal plots was the presence of narrow (few kilometers wide) channels of moisture extending 15–20 km into the dry air mass. Past studies have suggested that echo thin lines observed in the clear air can be used as a proxy for delineating the moisture contrast across the dryline. In contrast, the “moisture extrusions” were present even though the thin line was quasi-linear and were located in weak-echo regions along the thin line. It is hypothesized that transverse rolls developed at an angle to the boundary layer winds and intersected the dryline. The kinematic airflow associated with these rolls could have protected the moist tongues from the eroding effect of the dry flow west of the dryline. The moisture extrusions appear to diminish with time as they mix with the surrounding dry air.

1. Introduction
There has been an increased emphasis placed on understanding the initiation of deep convection during the summer months when large-scale forcing is weak or absent (e.g., Wilson et al. 1998). Indeed, Olsen et al. (1995) have shown a dramatic drop in the ability to forecast convection during the summer when major precipitation events occur. The main reason for this difference in skill is that winter season precipitation events are predominately associated with baroclinic disturbances that are well predicted by numerical forecast models. Fortunately, there have been important advances in warm season forecasting with the recognition that there is a strong relationship between convergence lines (e.g., synoptic-scale fronts, drylines, gust fronts, and seabreeze fronts) that develop within the boundary layer and convection initiation (e.g., Purdom 1982; Wilson and Schreiber 1986; Wilson and Mueller 1993). While these studies have led to major improvements in our ability to forecasts these events, it has been suggested that further gains in predictability would occur if high-resolution water vapor measurements in the boundary layer could be obtained (e.g., Emanuel et al. 1995; Dabberdt and Schlatter 1996; Weckwerth et al. 2004). Several recent studies have shown that inclusion of detailed water vapor measurements has improved our understanding of storm initiation (e.g., Sun 2005; Murphey et al. 2006; Fabry 2006; Roberts et al. 2008).

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Roger M. Wakimoto, NCAR/EOL, P.O. Box 3000, Boulder, CO 80307.
E-mail: wakimoto@ucar.edu

DOI: 10.1175/2009MWR2991.1

© 2010 American Meteorological Society
This paper documents the kinematic and thermodynamic structure of a dryline that developed on 11 June 2002 during the International H₂O Project (IHOP; Weckwerth et al. 2004). The dryline is a convergence boundary that separates hot, dry air from the Mexican plateau from the relatively cooler, maritime air from the Gulf of Mexico (Rhea 1966; Schaefer 1974, 1986). An airborne Doppler radar as well as a number of mobile research platforms converged on this boundary during the late afternoon. The airborne Doppler radar flew a box pattern around the dryline with along-boundary legs being ~90 km long. Accordingly, the variability of the wind field with high spatial resolution was well documented. No moist convection developed within the intensive observation region on this day as noted by Cai et al. (2006). Detailed wind, temperature, and moisture fields associated with this dryline, however, provide an extensive dataset that has only been available for a few case studies in the literature. The low-level moisture pattern was estimated using radar refractivity, a new technique using phase delay measurements from a Doppler radar (Fabry et al. 1997; Weckwerth et al. 2005; Roberts et al. 2008). The refractivity analysis reveals along-boundary variability of the moisture distribution that has not been previously documented.

An interesting aspect of this case was that the kinematic boundary associated with the dryline was the weakest of all of cases studied during IHOP. The moisture contrast across the dryline, however, was still large (3–4 g kg⁻¹). As a result, there is an opportunity to compare the relationship between the moisture field and the relative weak wind discontinuity associated with the dryline. Schultz et al. (2007) have shown the approximate linear relationship between surface confluence and moisture gradients across the dryline (see their Fig. 2). However, they also illustrate that drylines associated with intense moisture gradients can be associated with small, positive surface confluence.

Section 2 provides a brief overview of IHOP and the primary data platforms. The surface and radar analyses are presented in section 3. Section 4 describes the vertical structure of the dryline based on dropsondes and section 5 presents the dual-Doppler and radar refractivity analyses. The summary and conclusions are presented in section 6.

2. IHOP and the primary data platforms

The field phase of IHOP took place during the late spring and early summer of 2002 over the southern Great Plains of the United States. One of the main objectives of IHOP was to document the three-dimensional water vapor distribution in the lower troposphere in order to better understand the processes that lead to the initiation of deep, moist convection. Part of this objective was met by collecting moisture measurements within the convective boundary layer using a variety of remote sensing techniques (Weckwerth et al. 2004). It was concluded early in the planning stage that in order to sample a number of convergence boundaries, a majority of the observing platforms deployed during IHOP would have to be mobile. For more information about IHOP, the reader is referred to Weckwerth et al. (2004).

a. ELDORA

The Electra Doppler Radar (ELDORA) is a 3-cm airborne Doppler radar (Hildebrand et al. 1994) on board a Naval Research Laboratory (NRL) P-3 aircraft. The two antennas scan fore and aft of the normal to the fuselage of the aircraft by ~18.5°. ELDORA uses a multibeam scanning technique (Jorgensen et al. 1996) in order to collect data that can be used in a dual-Doppler wind synthesis. The scanning parameters for ELDORA are shown in Table 1. Convergence boundaries often appear as radar-detectable thin lines even in the absence of precipitation particles (e.g., Wilson and Schreiber 1986). ELDORA is the only scanning airborne Doppler radar with sufficient sensitivity that is capable of detecting these boundaries within the clear air (e.g., Wakimoto et al. 1996).

Research flight plans required the P-3 to fly at low levels [400–600 m above ground level (AGL)] hereafter, all heights are AGL except where indicated] and parallel to the thin lines. The thin line was positioned within 2–3 km from the aircraft and resulted in a box-type flight track approximately 90 km long. The flight track frequently required continuous corrections to the aircraft heading owing to the nonlinear nature of many of the boundaries. The long flight legs resulted in data that resolved the along-boundary variability of the convergence boundary over an extended path. In addition, the mean vertical structure of the dryline could be obtained by averaging individual cross sections from the dual-Doppler wind syntheses along the entire length of the flight track. The details of the radar methodology are presented in the appendix.
b. S-Pol

S-Pol is an S-band multiparameter radar (Lutz et al. 1995) that performed continuous surveillance scans at low levels every 5 min during IHOP and was equipped to record radar refractivity (in units of N). Refractivity can be derived by identifying ground targets that are located in the vicinity of the radar site and quantifying the small variations in the return phase from stationary targets caused by changes in the index of refraction in the intervening atmosphere (Fabry et al. 1997; Fabry 2004). Weckwerth et al. (2005) were able to show high correlation between radar refractivity and refractivity calculated from aircraft flying at low levels and surface mesonets during IHOP. Variations of refractivity are primarily owing to changes in water vapor under typical summertime temperatures (Fabry et al. 1997; Fabry 2004, 2006). High (low) values of N represent relatively moist (dry) air. The ability to map out the mesoscale variability of moisture using radar refractivity has been shown by Fabry (2006) and Roberts et al. (2008) and is currently being evaluated for possible operational implementation on the network of the Weather Surveillance Radar-1988 Doppler (WSR-88D) radar (Roberts et al. 2008).

3. Surface and radar analysis

An upper-level low was centered near the border between Montana and Canada at the 500-mb level resulting in southwesterly flow over the IHOP domain (not shown). At the surface, there was a low pressure area near the Oklahoma panhandle and southwestern Kansas (Fig. 1). A frontal zone associated with a wind shift was apparent over southwest Kansas and extended northeastward into Nebraska at 2100 UTC. A dryline extending from Kansas into the Oklahoma Panhandle is also evident as noted by Cai et al. (2006) (Fig. 1).

The sequence of satellite images with surface analyses superimposed (Fig. 2) reveals the lack of deep convection from 1900 to 2200 UTC. The black line in the figure shows portions of the NRL P-3 flight track (the entire flight track of the aircraft is shown in Fig. 3). The aircraft executed a spiral descent into the boundary layer (~600 m) from higher altitudes at ~1900 near the S-Pol radar (Figs. 2a and 3). The initial flight pattern was a rectangular boxlike pattern in an attempt to sample the stationary front and any dryline that might be present (Figs. 2b and 3). There was a diffuse moisture and wind...
gradient associated with the dryline in the region sampled by the aircraft but no sharp discontinuity was observed (not shown). Subsequently, the P-3 flew a smaller box pattern to the southeast of the stationary front around 2100 UTC (Fig. 2c) in anticipation of the formation of a well-defined dryline. A distinct thin line developed between 2100 and 2200 UTC and the aircraft initiated elongated box patterns along the boundary (Fig. 2d). The dryline was slowly retrograding during this time at 1–2 m s\(^{-1}\) based on an isochrone analysis (not shown).

Surface analyses superimposed onto surveillance scans from S-Pol at 2100 and 2200 UTC are shown in Fig. 4. The black arrow at both times denotes the developing thin line associated with the dryline although the echo is not clearly apparent in the region sampled by ELDORA (note the echo pattern near the flight track in Fig. 4b). The thin line denotes the position of maximum updrafts (e.g., Wilson et al. 1994) and can be regarded as the kinematic location of the dryline. A moisture gradient is apparent across the dryline in both the surface data and

---

**Fig. 2.** Surface analysis for (a) 1900, (b) 2000, (c) 2100, and (d) 2200 UTC 11 Jun 2002 superimposed onto visible satellite images. Virtual potential temperature (\(^\circ\)C) and mixing ratio (g kg\(^{-1}\)) are plotted. The stationary front and dryline are shown. The track of the P-3 is shown by the black line. The small box represents the location of the dual-Doppler analysis shown in Figs. 6 and 10. Wind vectors are plotted using the following notation: barb = 5 m s\(^{-1}\) and half barb = 2.5 m s\(^{-1}\).
radar refractivity plots in the figure. The green-, blue-, and magenta-colored region located northwest of S-Pol denotes a relatively dry air mass (i.e., low values of refractivity). The yellow- and brown-colored regions denote moist air. The increase in the moisture gradient across the dryline is also apparent when comparing the refractivity plots in 2100 and 2200 UTC. Note the increased prevalence of lower values of refractivity (blue and magenta colors) to the northwest of the dryline at the latter time.

4. Sounding cross section

A series of nine dropsondes were deployed by a jet flying at ~500 mb in an approximate northwest-to-southeast pattern between 2134:29 and 2156:37 UTC (Fig. 4b). The orientation of the cross section resulting from the dropsonde data was nearly perpendicular to the dryline and the frontal boundary. Two air masses can be identified in the vertical cross section shown in Fig. 5. The frontal and dryline boundaries are approximately delineated by the 317-K isentropes in the figure (also suggested by the 10 g kg$^{-1}$ isopleths of mixing ratio).

The top panel in Fig. 5 is a plot of the calculated convective available potential energy (CAPE) and convective inhibition (CIN). The CAPE attains a local maximum near the surface front, decreases to a minimum between the front and dryline, and then rises monotonically starting at the location of the dryline. The convective inhibition values reach a maximum in the intervening air between the two air masses. The average location of the level of free convection (LFC) is ~3 km (Fig. 5). It appears that the greatest potential for deep convection to develop was along the dryline if the updrafts could overcome the CIN. However, an impediment for rising parcels of air was the increased stability in the region between 3.8 and 4.8 km. Cai et al. (2006) has shown that the Oklahoma Panhandle was under the influence of midlevel subsidence on this day based on the National Centers for Environmental Prediction–National
Center for Atmospheric Research (NCEP–NCAR) reanalysis of 500-mb geopotential height and vertical pressure velocity ($v$). Stensrud and Maddox (1988) and Richter and Bosart (2002) have shown that larger-scale descent can prevent convection initiation even when large CAPE and conditionally unstable environments exist. The absence of wind speed and direction information from several dropsondes prevented an analysis of the two-dimensional frontogenesis structure of the current case.

5. Airborne dual-Doppler and radar refractivity analysis

The utility of using radar refractivity to estimate the moisture variability associated with boundary layer processes has recently received extensive scrutiny (e.g., Roberts et al. 2008). In the present case, the airborne Doppler wind analysis of the dryline was located near the S-Pol radar as shown in section 3. As a result, the present study provided one of the rare opportunities...
during IHOP when dual-Doppler wind syntheses could be combined with radar refractivity plots derived from low-level surveillance scans recorded by S-Pol.

a. 2121–2133 UTC

The first flight leg flown by the P-3 was used to determine the orientation of the boundary and to position the aircraft in the optimum position to collect high-resolution data on the fine line. The second flight leg was flown between 2121 and 2133 UTC when the P-3 was flying parallel to and northwest of the thin line. The thin line is better defined than the results shown in Fig. 4 with maximum radar reflectivities within the cell-like structures greater than 4 dBZ. A few pockets of updrafts with speeds >2 m s\(^{-1}\) can be identified and small confluence in the wind direction across the dryline is apparent (Fig. 6a). It should be noted that higher-resolution radar analyses would have resolved updrafts larger than 2 m s\(^{-1}\). The mean vertical structure of the dryline was created by averaging 110 cross sections along the boundary as described in the appendix (Fig. 7). The mean echo intensity associated with the thin line (<1 dBZ) was the lowest of all of the case studies investigated by ELDORA during IHOP. This observation suggests that the horizontal convergence across the boundary was weak based on the results from Wilson et al. (1994). Indeed, horizontal convergence (not shown) and updrafts averaged along the entire length of the thin line based on the wind syntheses (>0.5 m s\(^{-1}\)) were the smallest observed during IHOP (not shown). Small-scale circulations are also present along the boundary (Fig. 6a). The preceding discussion suggests that the 11 June dryline was associated with a relatively weak kinematic boundary.

There is a secondary circulation in the wind field in the top panel of Fig. 7 with weak downdrafts to the east of the dryline. The component of horizontal wind (\(v'\))

![Fig. 5. (top) Calculated CAPE and CIN values for a surface-based parcel for each sounding. (bottom) Northwest–southeast vertical cross section perpendicular to the dryline of virtual potential temperature (black lines, K) and mixing ratio values (gray lines, g kg\(^{-1}\)). The height of the LFC is shown by the dotted line. The locations of the soundings are shown by the dashed lines. The black box represents the approximate region for the dual-Doppler analyses shown in Figs. 6 and 10. Wind vectors are plotted using the following notation: barb = 5 m s\(^{-1}\) and half barb = 2.5 m s\(^{-1}\). The release points of the soundings are shown in Fig. 4 (except for the dropsonde released at 2134:29 UTC, which is located to the north of the region plotted in the figure). (top) The left (right) ordinate axis is for the CAPE (CIN) values.](image)
perpendicular to the dryline (bottom panel) reveals an acceleration of the flow over the thin line reflectivity maximum as would be expected owing to solenoidally generated circulation (e.g., Charba 1974; Atkins and Wakimoto 1997). Positive values of vertical vorticity (>0.5 $\times$ 10$^{-3}$ s$^{-1}$) were positioned on the western edge of the thin line. A broad but weak region of updrafts (bottom panel) can be identified as the westerly flow rises above the moist air located east of the dryline. The total horizontal wind (Fig. 7, bottom panel) reveals a slight veering of the wind direction with increasing height through the moist air mass.

The radar refractivity plot (Fig. 6b) illustrates dry air (low values of N) to the northwest of the dryline. The 2-dBZ isopleths outlining the position of the thin line are drawn to aid with the comparison of the analysis shown in Fig. 6a. There are relatively high values of N in the southwest section of the moist air mass (Fig. 6b). This moist air may have been advected into the region by an area of enhanced southerly flow that is apparent in Fig. 2c. The origin of the enhanced flow is not known.

The plot of N suggests large along-boundary variation of moisture. Prominent in the refractivity plot are two extrusions of high N values highlighted by the black arrows. This analysis suggests that moist air is extending to 15–20 km to the northwest of the thin line. The length of these channels of high moisture is nearly an order of magnitude greater than those previously documented in the literature (e.g., Pietrycha and Rasmussen 2004; Buban et al. 2007; Ziegler et al. 2007a). The moisture extrusions presented here appear to be different than the wavelike undulations along the dryline documented by McCarthy and Koch (1982) and Ziegler et al. (2007b). It might be expected that these moisture extrusions would have difficulty persisting under the influence of a strongly heated and well-mixed convective boundary layer west of the dryline. A possible explanation is that transverse rolls developed at an angle to the boundary layer winds and intersected the dryline. The red arrows in the reflectivity plot in Fig. 4b denote the locations of roll-like features that are transverse to the boundary layer wind direction. The average spacing of the rolls in Fig. 4b is $\sim$7 km. This separation is close to the spacing of the moisture extrusions shown in Fig. 6b. In addition, the orientation of these rolls is consistent with the major axis of the extrusions. Roll-like features interacting with convergence boundaries in the convective boundary layer have been documented in the literature (e.g., Atkins et al. 1995; Dailey and Fovell 1999; Weckwerth et al. 2008). The kinematic airflow associated with these rolls could have protected the moisture...
tongues from the eroding effect of the hot, dry flow west
of the dryline. Fabry (2004) and Weckwerth et al. (2005) have sug-
gested that refractivity can be associated with errors
related to nonstationary targets and swaying vegetation.
The in situ data collected at flight level provided an
opportunity to verify the existence of the moisture extru-
sions rather than being an artifact to fit refractivity
retrieval technique. A time plot of in situ measurements
of mixing ratio along the flight track has been super-
imposed onto the refractivity analysis (Fig. 6b). The
comparison must be viewed with some caution since the
aircraft measurements are collected along a line at high
resolution while the refractivity values are averaged
over radar volume (Weckwerth et al. 2005). Apparent in
the figure is the relationship between the moisture extru-
sions and the large increases in mixing ratio (>3 g kg\(^{-1}\)).
It should be noted that the optimum flight track to
sample the extrusions would have been parallel to and to
the northwest of the actual path shown in the figure.

Another time plot of the mixing ratio is presented in
Fig. 8. The figure reveals that the moist regions were
associated with potentially cool air. This observation
suggests that local solenoids oriented along the axis of
the moist tongues would promote diffluence along the
extrusions and entrainment of dry air into the moist air.
The existence of transverse roll circulations extending
across the dryline (Fig. 9), however, would promote
confluence of moisture along the center axis of the ex-
trusions (drawn in red) and allow them to persist against
the shear and mixing within the dry air. Support for this
possible scenario has been presented by Hane et al.
(2002). They suggest that boundary layer roll circula-
tions at an angle to the dryline can maintain or increase
low-level moisture and promote cloud formation within
the moist and dry air. The exact depth of the moisture
extrusions shown in Fig. 9 is not known. Accordingly,
the schematic model presents an approximate height.
The only estimates suggest that they extend at least as
high as the flight level of the aircraft.

Close examination of the positions of the “fingers” of
moisture extending into the dry air mass (Fig. 6a) reveals
that they were located close to the weak-echo regions
between the 2-dBZ reflectivity cores (Fig. 6b). Hane
et al. (2002) proposed that all thin lines were associated
with gradients of moisture. Past studies largely support
this conclusion, however, the present case illustrates that
a well-defined (and approximately linear) thin line may
not accurately delineate the moisture gradient.

The results presented in the previous paragraph pro-
vide further evidence of the value of radar refractivity in
defining the horizontal distribution of the moisture field
within the boundary layer. The present case is also im-
portant since it documents the detailed structure of a
relatively weak kinematic convergence boundary that is
associated with a large moisture gradient. Indeed, the
difference in mixing ratio across the dryline on 11 June
was comparable to other studies (e.g., Crawford and
Bluestein 1997; Atkins et al. 1998; Ziegler and Rasmussen
1998). Narrow moisture extrusions ~15–20 km into the
dry air mass (Fig. 6b) could be a common characteristic
of drylines that have not been previously resolved owing
to the lack of comprehensive water vapor measurements;
however, it is also possible that they are predominately
associated with drylines that are associated with rela-
tively weak kinematic discontinuities.

b. 2156–2204 UTC

The fourth leg flown along the dryline from 2156 to
2204 UTC provided another opportunity to examine the
kinematic structure of the dryline and its relationship to
the moisture field (Fig. 10). The thin line structure is
similar to the previous analysis time (Fig. 10a). The
vertical velocity and vorticity fields have not changed
substantially and the wind shift across the convergence
boundary is not distinct. Fingers of moisture extending
into the dry air mass are still apparent in the radar

![Fig. 7. Mean vertical cross section perpendicular to the dryline for 2121:52–2133:05 UTC 11 Jun 2002. (top) Radar reflectivity
(dBZ) is plotted as gray lines. Vertical vorticity (10^{-3} \text{s}^{-1}) is
plotted as black lines. Vertical velocities and component of hori-
zontal flow in the plane of the cross section are plotted as black
arrows. (bottom) Positive and negative values of vertical velocity
(m s^{-1}) are plotted as black and dashed lines, respectively. Component of horizontal flow (m s^{-1}) perpendicular to the boundary is
plotted. Positive (westerly) flow is shown by the gray lines. The
total horizontal wind vectors are plotted. The rotated coordinate
system is shown in the inset in Fig. 3.](image-url)
refractivity plot (Fig. 10b); however, these extrusions are not as pronounced as those shown in the previous analysis time (Fig. 6). The locations of two prominent moisture features are highlighted by the black arrows in Fig. 10b. The existence of these two moisture extrusions identified in radar refractivity is confirmed by examining the in situ data collected at the flight level of the mixing ratio. The mixing ratio data collected during this time are less than the values shown in Fig. 6 even though the range of refractivity values is approximately the same. This difference is owing to the higher altitude of the aircraft during this segment of the flight leg where the mixing ratio values were smaller. Another contributing factor is the difference that occurs when comparing aircraft measurements along the flight path versus refractivity values averaged over a radar volume mentioned earlier.

The moisture extrusions are, once again, approximately positioned near the weak-echo regions between the 2-dBZ isopleths. The results presented in this paper generally support the relationship between the location of reflectivity thin lines in the boundary layer and updraft regions proposed by Wilson et al. (1994). However, the thin line may not be an accurate proxy for the location

---

**FIG. 8.** In situ data collected at flight from 2123 to 2130 UTC. Virtual potential temperature (dashed line), mixing ratio (black line), and wind direction (dotted line) are plotted. The black arrows denote the periods when the aircraft penetrated the moisture extrusions.

**FIG. 9.** Schematic model illustrating the structure of the dryline on 11 Jun 2002. The moisture extrusions are highlighted by the black arrows. Circulations (in red) that would be associated with transverse roll circulations are shown. The approximate position of the axis of confluence associated with the rolls is drawn.
of the strongest moisture gradients as shown in Figs. 6 and 10 contrary to the results discussed by Hane et al. (2002). Of course, the latter study was largely based on data recorded by surface stations and aircraft penetrations of numerous drylines, which does not provide sufficient spatial and temporal continuity of the moisture field. The dryline on 11 June was not associated with a prominent kinematic discontinuity. Stronger kinematic discontinuities may yield a stronger relationship between thin lines and moisture gradients.

The evolution of the moisture gradient as defined in the radar refractivity plot and the thin line is illustrated in Fig. 11. The thin line is quasi-linear and is slowly retrograding during this time interval. In contrast, the moisture pattern undergoes large variations during this time. The moisture gradient across the dryline reveals substantial along-boundary variability at the early times (Fig. 11a). Subsequently, the moisture undulations decrease at later times (e.g., Fig. 11c). Note that one of the moisture extrusions (highlighted by the black arrow in Fig. 11) appears to diminish as it mixes with the surrounding dry air.\(^1\) The mean position of the maximum refractivity gradient approaches the fine line position during this period. The results shown in the figure reveal a more complex relationship between the distribution of moisture and the kinematic location of the dryline as indicated by the thin line than has been previously documented.

\(^1\) Examination of a series of surveillance scans recorded every 5 min reveals that the moist tongue, highlighted by the black arrow, was moving uniformly to the northeast as a coherent feature.

6. Summary and conclusions

An analysis of a dryline on 11 June 2002 that did not initiate deep, moist convection in the region studied was presented. The present case is important since it provides one of the few opportunities to combine detailed dual-Doppler wind syntheses with the moisture fields estimated from radar refractivity. The dryline was the weakest kinematic boundary observed during IHOP but was associated with a large moisture gradient (3–4 g kg\(^{-1}\)).

Mean dual-Doppler vertical cross sections revealed a secondary circulation as the ambient air accelerated over the moist air mass east of the dryline. The kinematic position of the dryline was denoted by a radar thin line, which was quasi-linear during the analysis time. In contrast, the moisture pattern across the dryline was more complex than was suggested by the characteristics of the thin line. Prominent in the radar refractivity analysis was the presence of narrow “fingers” of moisture extending 15–20 km into the dry air mass (referred to as moisture extrusions). These moisture extrusions suggest caution when relying on radar thin lines as a proxy for the location of the moisture gradient. The present case may be an exception and related to the fact that the kinematic discontinuity across the dryline was the weakest of any case studied during IHOP. It is hypothesized that the existence of transverse rolls is a plausible explanation why the narrow moist tongues could extend 15–20 km into the dry air mass. The moisture extrusions appear to diminish with time as they mix with the surrounding dry air. Future studies are needed to examine the relationship between moisture discontinuities and kinematic characteristics of...
convergence boundaries. The present case suggests a more complex relationship than has been previously documented.

Acknowledgments. Research results presented in this paper were partially supported by the National Science Foundation under Grant ATM-021048. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation. The comments from three anonymous reviewers and the editor substantially improved an earlier version of this manuscript.

APPENDIX

Radar Methodology

The radar data was edited and the aircraft motion was removed from the velocity fields using the SOLO II software package (Oye et al. 1995). The data was then corrected for navigational errors using a technique developed by Testud et al. (1995). The along-track and sweep-angle resolution for ELDORA during IHOP was $\sim 550$ m and $1.5^\circ$, respectively, based on the information presented in Table 1. This led to an effective sampling in the vertical of $\sim 250$ m at a distance of 10 km from the radar. The data was subsequently interpolated onto a grid with a horizontal and vertical grid spacing of 600 and 300 m, respectively. A Cressman filter (Cressman 1959) was applied during the interpolation process with a radius of influence of 600 m in the horizontal and 450 m in the vertical. The lowest level was chosen to be 400 m AGL. The refractivity data was averaged over a 4-km region for each grid point based on the results from Weckwerth et al. (2005).

The synthesis of the radar data was performed using the Custom Editing and Display of Reduced Information in Cartesian Space (CEDRIC; Mohr et al. 1986). A three-step Leise filter (Leise 1982) was applied to the Doppler wind field. This type of filtering removes wavelengths less than 4.8 km. No correction for hydrometeor fall speeds was applied since the echo returns were collected in the clear air and were relatively weak. Vertical velocities were derived from an upward integration of the horizontal convergence field using the anelastic continuity equation. An estimate of the vertical velocity below the lowest grid level is based on the scheme proposed by Nelson and Brown (1987). The maximum errors associated with the vertical velocities are estimated to be less than 1–2 m s$^{-1}$ (Wilson et al. 1994). All wind fields presented in this paper are ground relative.

The vertical structure of the dryline was reconstructed by averaging 110 dual-Doppler cross sections for each flight leg. The extensive averaging effectively removes the along-boundary variability. The errors in the vertical velocity patterns are reduced in these mean vertical cross sections.

REFERENCES


