Observations of the Afternoon Transition of the Convective Boundary Layer

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ABSTRACT

This manuscript uses 915-MHz wind profiler reflectivity and Doppler spectral width data in time versus altitude to characterize general behaviors of the ending of the daytime convective boundary layer. From a wide variety of observed patterns, two categories are identified: inversion layer separation (ILS) and descent. Several possible causes for the different shapes of the patterns are discussed. Results show the descent cases occur on relatively warm and moist days with weak turbulence and a weak capping inversion and ILS days occur on cooler and drier days with stronger turbulence and a stronger temperature capping inversion. The time at which the transition begins is also investigated and is found to be variable, sometimes beginning several hours before sunset.

1. Introduction

The boundary layer is interposed between surface and near-surface sources of heat, water vapor, momentum, and pollutants and the rest of the atmosphere. Boundary layer physics controls how those quantities are transported both horizontally and vertically on all scales. The behavior of the atmospheric boundary layer during the period between the fully developed convection of midday and the stable conditions of the nocturnal boundary layer is poorly understood but is of interest in several fields, including chemical and pollutant modeling.

In this study, radar wind profiler data are used to characterize the afternoon transition and subsequent residual layer behavior. We are interested in answering the following questions about the afternoon transition: what is the shape of the convective boundary layer (CBL) during the transition, how variable is the CBL behavior, and at what time does the transition begin?

Several studies of the afternoon transition have been conducted, both observational (Kaimal et al. 1976, Grant 1997) and modeling (Nieuwstadt and Brost 1986; Sorbjan 1997). Beginning with a well-mixed CBL and a strong capping inversion, common features seen in these studies include a capping inversion that remains at a constant height during the afternoon, even as the surface heat flux decreases; evidence that small-scale eddies decay earlier than large-scale ones; and entrainment continuing at the top of the CBL, even after the surface sensible heat flux has become negative. However, although consistent features have been observed within the afternoon transition, it remains a complex problem, exhibiting much more variability than is seen in the morning transition.

2. Experiment layout and instrumentation

The Flatland experiments were located in an extremely flat area southwest of Champaign–Urbana, Illinois, planted with approximately equal amounts of soybeans and corn. The two campaigns discussed in this paper are Flatland95, which was from 1 August to 30 September 1995, and Flatland96, which operated from 15 June to 23 August 1996. During each of these campaigns, a triangle of three similarly instrumented sites was established. The sides of the triangle were 5.7, 7.5, and 7.6 km in length. The land inside the triangle was flat to within 5 m, and the site elevations differed by less than 2 m. A detailed description of the sites and the 1995 and 1996 boundary layer experiments is given by Angevine et al. (1998, 2001).

In this paper, we present results from the Flatland Atmospheric Observatory (FAO) site at which a 915-MHz profiler, a laser ceilometer to detect the presence and altitude of cloud, and a surface meteorological station were operated. A second 915-MHz profiler was located at the Monticello Road site, 7 km to the southwest of FAO. The reflectivity figures from Monticello Road and FAO were compared to establish that the results from the FAO site were not specific to this site, but rather that the observed behaviors were occurring over a larger region. The agreement was extremely good, which gives confidence in the representativeness of the results from the FAO site.

Vertical profiles of temperature, humidity q, wind

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speed, and wind direction were obtained at 1200 LST each day using a Vaisala, Inc., RS80-15LH radiosonde. On days when a well-developed boundary layer was expected to form, additional radiosondes were launched at 0900, 1030, and 1330 LST. Because examination of the afternoon transition was not one of the specific goals of the Flatland experiments, very few radiosondes were launched after 1330 LST.

For the 1996 campaign, a Flux–portable automated mesonet (PAM) station from the National Center for Atmospheric Research was deployed a little under 800 m west of the FAO profiler in an adjacent cornfield. This location was selected to maximize the homogeneous fetch for as much of the full circle of wind directions as possible while still remaining close to the FAO instrumentation. The Flux–PAM determined sensible and latent heat and momentum fluxes at several meters above the canopy and measured wind speed and direction at 10 m AGL, temperature and relative humidity at 2 m AGL, pressure, rainfall, soil temperature, heat flux, and net and incoming solar radiation.

Surface analysis maps from the National Centers for Environmental Prediction were also examined for each of the selected days. These maps provide information on surface conditions such as wind speed and direction, temperature, pressure, cloud cover, and the locations of frontal zones. This information enabled us to compare weather conditions prior to and during each of the days.

3. Wind profiler measurements

Wind profilers are sensitive Doppler radars, designed to respond to refractive index fluctuations in clear air. Reflectivity (range-corrected signal-to-noise ratio) is a well-established product of wind profilers and has been shown to provide an accurate measurement of CBL height during the day (Cohn and Angevine 2000; Grimsdell and Angevine 1998; Angevine et al. 1994). Large values indicate the presence of turbulence or strong gradients in refractive index. Within the boundary layer, the major influence on refractive index is humidity, although temperature is also important. A strong reflectivity layer observed at the top of the boundary layer, indicating the CBL height, is due to turbulence and humidity gradients from the humid lower layer to the drier air of the free troposphere (White et al. 1991). We present the reflectivity on an arbitrary scale (Figs. 1, 2) because calibrating profilers is extremely difficult and usually unnecessary.

The profilers used in this experiment were developed at the National Oceanic and Atmospheric Administration Aeronomy Lab (Carter et al. 1995; Ecklund et al. 1988). They are transportable systems that have been deployed during a large number of meteorology and atmospheric chemistry experiments and in long-term studies in the Tropics.

During the Flatland experiments, the profilers operated at 60-m vertical resolution with the first range gate at 150 m AGL. However, returns from the lowest range gates are always difficult to interpret because only the upper portion of any structures present at these altitudes will be seen. Returns below the third range gate at 270 m AGL were also unreliable in this case because of a minor hardware malfunction at the FAO site. Six beam positions, four oblique beams in two coplanar pairs and two vertical beams of orthogonal polarization, were used. This configuration allows both the horizontal and vertical wind speeds to be measured. The dwell time on each beam was approximately 25 s.

Doppler spectral width was also used to examine the afternoon transition. The width was obtained from each 25-s wind measurement. During this time period, a range of wind velocities is measured within the profiler sample volume, and the width of this spectrum is the Doppler spectral width.

Because hard targets such as hydrometeors, birds, aircraft, and insects also produce a strong return, we have excluded days with noticeable rainfall and used processing software that includes an intermittent contamination removal algorithm (so-called bird algorithm) to remove the effect of contamination from such objects (Merritt 1995).

During several of the evenings at the end of the 1995 campaign, a strong signal in both reflectivity and Doppler spectral width was seen after approximately 1900 LST (Fig. 1). The probable cause of this increased signal is the annual bird migration. Wilczak et al. (1995) show that birds can cause high returns in the profiler measurements, and bird migration is known to occur at night at this time of year near the FAO site (Warnock et al. 1995). The contamination did not affect the time of day in which we were interested for this research.

4. Data selection

The full-resolution profiler reflectivity provided a detailed record of the evolution of the CBL throughout the day. A total of 126 days of data were collected during the two Flatland campaigns. Of these, 25 days were rejected because of the presence of large sections of missing data or periods of rain during the afternoon, and 4 other days had no CBL development because of very heavy cloud cover or fog all day. On the remaining 97 days, a wide variety of patterns was seen. It was clear that there was no single consistent behavior, but each day was examined subjectively to see whether any repeated patterns occurred during the transition.

From this examination we established the following conditions that had to be met for inclusion in the study.

1) The reflectivity pattern showed growth of the CBL during the morning, and the Doppler spectral width showed a corresponding increase that indicated the presence and growth of boundary layer thermals.
2) During the afternoon, a discernible and coherent pattern could be seen in the reflectivity figure. The

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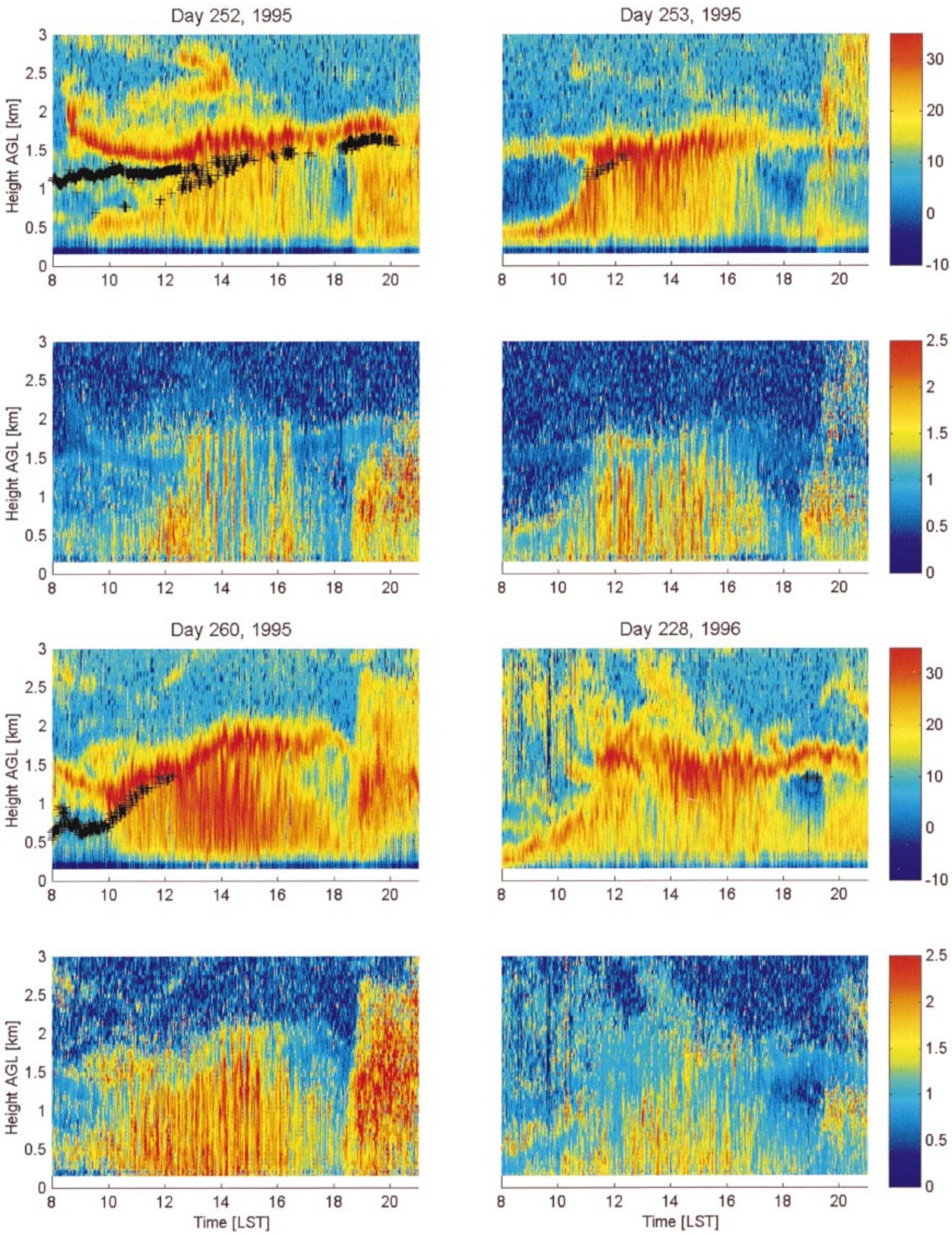

FIG. 1. Full-resolution reflectivity (upper panel of each quadrant) and Doppler spectral width (lower panel) in meters per second from the wind profiler for 4 days in the ILS category. Cloud measurements from the ceilometer are shown as black crosses on the reflectivity figure. Note that, during the afternoon of day 228 of 1996, although the ceilometer records no cloud, the solar radiation measurement indicates that there is, in fact, cloud present.

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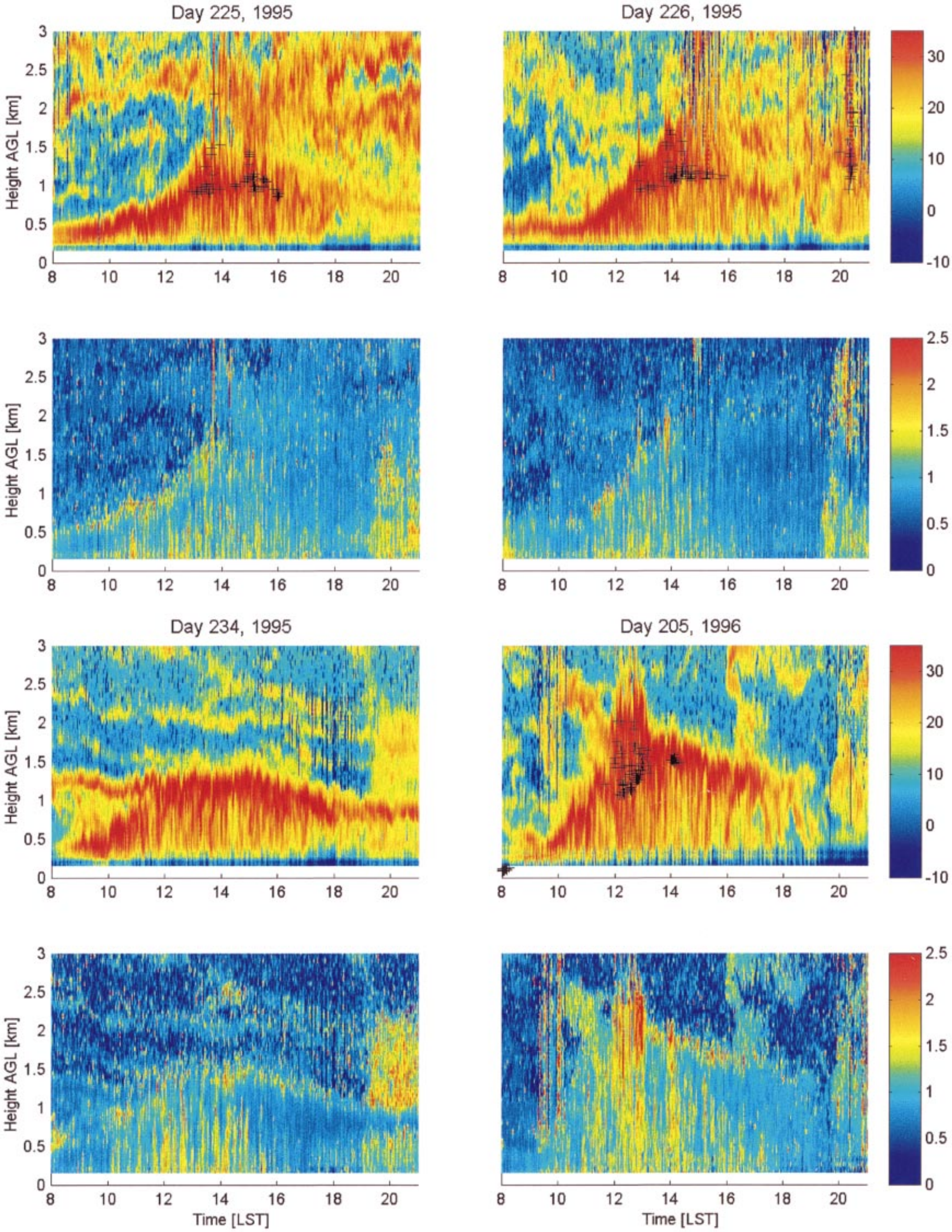

FIG. 2. As in Fig. 1 but for the descent category.

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Doppler spectral width showed a similar pattern, indicating that the reflectivity indeed was related to turbulent activity within the CBL.

A further 21 days were removed from consideration after failing to meet these criteria because of very poor CBL development even in the absence of rainfall. Exclusion of these days left a total of 76 days of data.

5. Characteristics of the transition

As was previously mentioned, much variation was observed in the behavior of the CBL during the afternoon and early evening, in contrast with the consistency seen during the morning transition. Nevertheless, on 25% of the 76 selected days (19 days) two distinct patterns or categories of behavior with well-defined characteristics were apparent. The definition of two categories and the assignment of particular days to those categories based on two-dimensional patterns was necessarily subjective. Although it may be possible to describe these patterns with a small number of objective parameters, we did not do so; such pattern recognition is a notoriously difficult problem.

The two categories were named *inversion layer separation* (ILS) and *descent,* based on the behavior of the profiler reflectivity in each category. The defining characteristics of the categories are as follows.

1) Inversion layer separation—days 241, 252, 253, 257, 260, 267, 269 1995; 200, and 228 of 1996:

   Profiler reflectivity was strong throughout the CBL depth during the morning, with correspondingly large Doppler spectral width, implying the presence of strong convection. The afternoon behavior was characterized by the persistence of strong profiler reflectivity at the height of the top of the late-morning CBL. Below this height was a region of weaker reflectivity and Doppler spectral width (a minimum). Then, extending from the ground up to a gradually decreasing maximum height below this minimum, the reflectivity and Doppler spectral width were again strong, although weaker than in the morning.

2) Descent—days 218, 225, 226, 227, 228, 232, 234, 236 1995; 205, and 235 of 1996:

   During the morning the reflectivity pattern showed CBL growth similar to that on the ILS days. However, despite this strong reflectivity, the Doppler spectral width was smaller, indicating weaker turbulence. From early afternoon to midafternoon, the maximum height reached by the strong reflectivity steadily decreased (similar to the pattern seen in the ILS days below the former top of the CBL) while the signal strength remained constant and the Doppler spectral width remained small. There was no evidence of the persistence of an upper-level band of strong reflectivity as on the ILS days.

The full-resolution reflectivity and Doppler spectral width are shown in Figs. 1 and 2 for some of the days in each category. The very fine vertical streaks seen in these figures are due to the time resolution of the profiler. These figures highlight the variability present within the categories but also show that, despite this variability, the basic features described above still can be seen. As an example from the ILS category, on day 252 of 1995, we see the CBL increasing in depth during the morning until reaching the residual inversion from the previous day at about midday. The CBL depth then remains constant until, at about 1600 LST, the thermals begin to stop short of reaching the inversion. Both the reflectivity and Doppler spectral width weaken and the maximum height of the convection decreases until about 1800 LST. At the height of the former top of the CBL, a coherent band of reflectivity remains visible throughout the afternoon. In the descent category, we see a similar pattern of CBL growth during the morning of day 225 of 1995, although the Doppler spectral width is smaller. The inversion-layer depth remains constant for a short time around midday then steadily decreases throughout the remainder of the afternoon. Although the Doppler spectral width is small, strong reflectivity below the top of the CBL continues to occur. Several more examples of daytime reflectivity patterns are shown by Angevine et al. (1998).

6. Discussion

Information from the ceilometer, surface weather maps, meteorological instruments, radiosondes, and PAM stations (where available) was examined to see whether there were any differences in the measured variables that could explain the observed differences in reflectivity between the two categories.

One of the more obvious forcing mechanisms on CBL behavior is cloud cover, but our findings suggest that it is not a major influence in this study. Table 1 includes information on cloud cover for each category. The total cloud fraction was very similar in each category (15% for ILS and 11% for descent), but there was a different pattern of cloud cover in each category. Cloud on descent days tended to concentrate during the early-afternoon hours (1200–1600 LST), and the cloud fraction during that period was greater than on the ILS days (14% vs 8% for ILS). One possible explanation for this pattern is that, during the early afternoon, higher humidity on the descent days may have lead to the formation of more fair-weather cumulus clouds.

Large-scale weather systems can have a strong influence on boundary layer behavior, but in our study the influence was minor. In the region around the FAO site during the summer, it is common for weak cold fronts to approach from the northwest but then either to dissipate or to retreat. Temperature and pressure differences across the cold fronts usually are small, with the main defining characteristics being a change in wind direction

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TABLE 1. Category comparison. The entrainment zone (EZ) limits used in the calculation of $\Delta\theta_v$, Δq, Ri_B, and wind shear were selected by hand from the radiosonde profiles for each day. Wind shear was calculated using the average wind speed in the segments 100 m above and below EZ (vertical resolution is 60 m). Three of the categorized days did not have profiler data available at this time. Temperature and RH are from the surface meteorological station, and cloud fraction is measured by the ceilometer.

	ILS	Descent
Total days	9	10
Days in 1995	7	8
Days in 1996	2	2
Mean days since rain	5.3	3.9
Median days since rain	3	4
0800–1800 LST		
Days with rain	0	0
Days with cloud	8	8
Cloud fraction (%)	15	11
1100–1200 LST		
Wind shear across EZ [m s^{-1} (100 m)$^{-1}$]		
Mean	1.03	0.59
Max	2.23	1.04
Min	0.05	0.27
Std dev	0.8	0.3
Ri_B across EZ		
Median	4.5	2.3
Max	225	10.3
Min	0.5	0.5
1200 LST radiosonde		
CBL $\Delta\theta_v$ (°C)	3.5	0.7
CBL Δq (g kg^{-1})	−3.3	−4.3
Mean CBL height (m)	1347	877
Min CBL height (m)	878	589
Max CBL height (m)	1745	1150
1200–1600 LST		
Cloud fraction (%)	8	14
Mean temperature (°C)	25.4	31.1
Min temperature (°C)	17.1	26.3
Max temperature (°C)	33.7	34.3
Mean RH (%)	41.2	63.0
Min RH (%)	18.4	42.6
Max RH (%)	64.9	79.4

TABLE 2. Comparison between one day in each of the categories. Calculations were made as for Table 1.

	253 (ILS)	226 (descent)
Days since last rain	3	5
Cloud fraction (%)		
0800–1800 LST	3.2	5.7
1200–1600 LST	0	12.5
1100–1200 LST		
Wind shear across EZ [m s^{-1} (100 m)$^{-1}$)]	0.3	0.7
Ri_B across EZ	56	0.8
1200 LST radiosonde		
CBL $\Delta\theta_v$ (°C)	2.96	0.53
CBL Δq (g kg^{-1})	−6.5	−6.1
CBL height	1445	699
1200–1600 LST		
Mean temperature (°C)	22.6	33.4
Min temperature (°C)	20.9	32.6
Max temperature (°C)	23.5	34.2
Mean RH (%)	43.9	71.8
Min RH (%)	41.1	69.5
Max RH (%)	51.9	76.6

and a drop in the dewpoint temperature behind the front. During our study, weather conditions were generally settled during the selected days. The main differences were that the ILS days were influenced more strongly by high pressure systems and that there was also a consistent difference in wind direction. On ILS days, the wind came from the north or northeast when a direction was discernible at all; on descent days, the wind was from the south.

One possible explanation for a persistent elevated band of reflectivity is the absence of strong wind shear, which prevents strong gradients in the capping inversion from being diminished by mixing even after disconnection from the surface. Our observations showed that although the wind shear was slightly larger in the ILS category, particularly during the morning, in absolute terms it was small in both categories. The strong capping inversion established in the ILS category (as seen in Fig. 3) combined with the weak shear may have contributed therefore to the prolonged persistence of the band of reflectivity. The same effect did not occur in the descent case because the capping inversion was weak.

The bulk Richardson number Ri_B was calculated over the same altitude range and days as the wind shear, using the 1200-LST radiosonde launch. As indicated in Table 1, Ri_B was generally lower in the descent category than in the ILS, indicating a higher probability of turbulence on descent days. These results support the idea that there was much less mixing on ILS days to remove the strong gradient whereas descent days were more likely to have any gradient mixed away.

A significant difference between the categories was the reflectivity, which is stronger in warm, humid environments. These conditions prevailed in the descent category. On ILS days, both temperature and humidity were lower, as shown in Table 1. Most of the ILS days occurred near the end of the campaign (day 241 is 29 August) when crops became senescent and surface moisture sources therefore were reduced significantly, whereas the descent days were earlier in the year. Lower temperatures observed on ILS days probably were attributable to decreased solar radiation at that later time of the year.

Differences in temperature and humidity affect energy partitioning. In moist conditions, more energy is partitioned into latent heat flux, leading to weaker convection. This effect is consistent with the formation of a weak capping inversion that was present in the descent case (Table 1). It is also consistent with the fact that the average CBL depth of descent days was low, around 880 m, in comparison with 1350 m for ILS, and that

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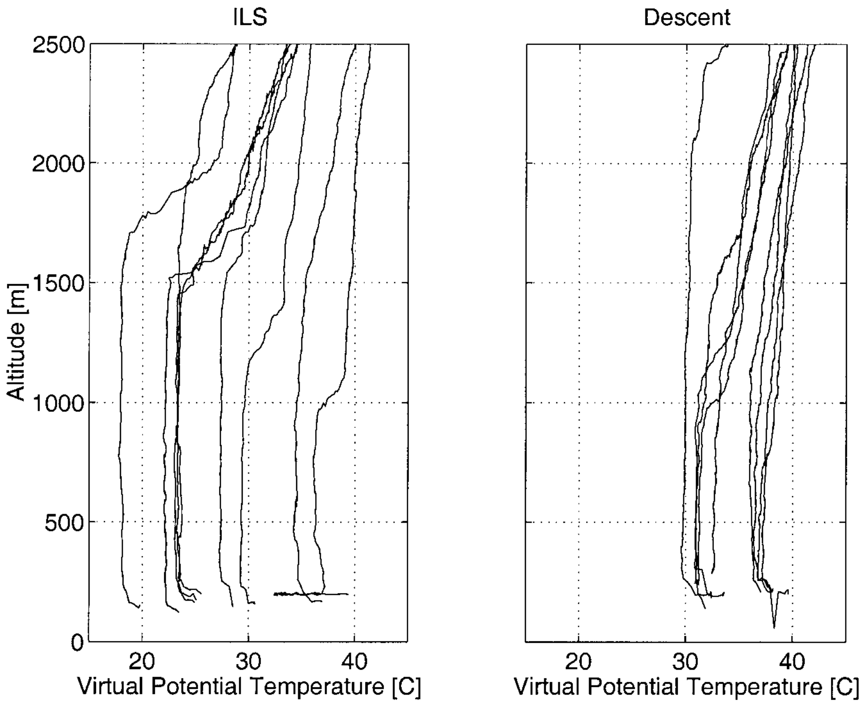

FIG. 3. Virtual potential temperature profiles (θ_v) for each of the categorized days calculated from the 1200 LST radiosonde measurement. The profiles have been smoothed slightly using a six-point moving-average filter.

the CBL did not stabilize in height but made a transition directly from increasing to decreasing, with the decrease in depth of the boundary layer beginning early in the afternoon.

PAM stations provided direct measurement of the surface sensible and latent heat fluxes on 3 days: 1 day from the descent category and two days from ILS. The descent day had larger latent heat flux and smaller sensible heat flux than the ILS days, indicating a smaller value of the Bowen ratio during the day. This result was consistent with the more moist and less turbulent conditions suggested by other measurements. On the ILS days, the sensible heat flux remained positive until much closer to sunset, supporting the idea that convection may continue later into the afternoon in this case.

In summary, our results showed the descent days to be warmer and moister than the ILS days, with a weaker capping inversion. Convection during descent days was less vigorous, which led to fewer clouds, a lower CBL depth, and earlier fading of the CBL. Wind shear was small in both categories.

7. Case studies

We have selected two example days to illustrate how an individual day fits into the general categories we have developed. The selected days are day 253 of 1995 (10 September) from the ILS category and day 226 of 1995 (14 August) from the descent category. These days are fairly typical examples of each category, as can be seen from the full-resolution reflectivity and Doppler spectral width figures (Figs. 1, 2). The same parameters are given for each day in Table 2 as are shown for the categories in Table 1.

During the morning of day 253, there is a small amount of cloud present at the top of the CBL but the afternoon is clear. In contrast, day 226 has cloud present only between 1200 and 1600 LST. Day 253 is cooler and has lower relative humidity, even though the length of time since the previous rainfall is less for that day (3 days) than for day 226 (5 days) and the amount of rain that fell was greater.

The wind shear across the entrainment zone is larger on day 226 than on day 253, contrary to the pattern seen in the category averages. A relatively small value of Ri_B was seen on day 226, so that on this day there may have been some light turbulence across the entrainment zone that would contribute to the removal of any gradients. A much larger value of Ri_B was seen on day 253.

The radiosonde profiles show day 253 to have a deeper CBL than does day 226, with a stronger temperature inversion. The relative humidity difference across the entrainment zone is very similar between these two days, as it was between categories (Table 1). Because the descent days are more humid within the CBL, this difference indicates that the free troposphere above the CBL is also more humid. This result implies that con-

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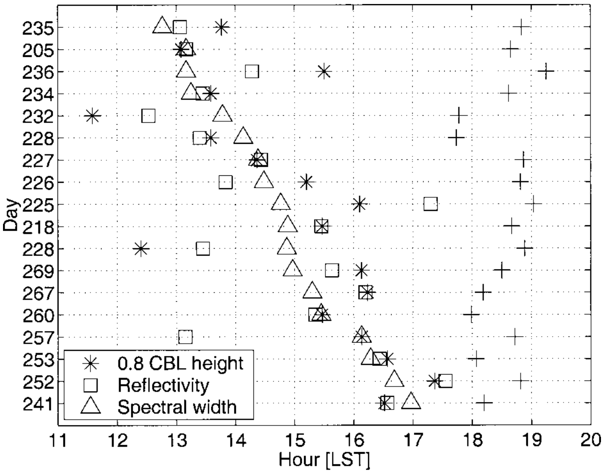

FIG. 4. Transition start times estimated using three different approaches as described in the text. The days are ordered according to the start time estimated from the Doppler spectral width figures. Sunset times for each day are shown as plus symbols.

ditions within the CBL may have an influence on the upper-level atmosphere even in conditions in which the cloud fraction is low and there are no large local venting events such as thunderstorms.

8. Transition timing

It has been assumed previously that the time at which the afternoon transition occurs is approximately an hour before sunset. We investigated the start time using three different approaches. The results are shown in Fig. 4.

The first estimate was derived from the full-resolution reflectivity figures for each day. On ILS days, the start time was taken as the time at which the upper band of increased reflectivity separated from the lower-level signal. For descent days, the transition was considered to have started when the CBL depth began to decrease. A second estimate of start time was obtained by applying these same criteria independently to the Doppler spectral width figures.

To obtain a more objective method, we reduced the amount of information considered. Using the Doppler spectral width, the resolution was degraded to 10-min time intervals. The data were also binned in altitude; only one bin, containing altitudes between 0.775 and 0.825 of the altitude of the top of the CBL at 1500 LST, was examined.

We expected the Doppler spectral width to be much larger above the CBL than within it because of the turbulence from convection within the CBL. The transition start time then could be identified as the time at which there was a sharp decrease in both the absolute value and the variability of the Doppler spectral width in the selected altitude strip. This pattern indeed was seen on all days except day 200 of 1996 (18 July), in which case a start time could not be determined using this method because of unusually small variations in the averaged Doppler spectral width throughout the day. The method was used to obtain a start time subjectively for the other days.

Figure 4 shows that, in general, each of the three approaches produced start times that were in good agreement. This result implies that the Doppler spectral width and profiler reflectivity are correlated well on individual days, with strong reflectivity generally indicating strong turbulence in the upper CBL. The actual transition start times varied widely in relation to sunset, with several of the days beginning the transition in the very early afternoon.

9. Summary

The objective of this study was to investigate some basic features of the afternoon transition. This investigation included a study of how variable the behavior of the CBL was during this period, what patterns of behavior could be identified and what the main influences were on each pattern, and at what time the transition began.

The growth of the CBL during the morning transition is fairly consistent, but this consistency was not seen in the afternoon. Wind profiler reflectivity and Doppler spectral width measurements revealed that there was, in fact, a wide variety of CBL behavior in the afternoon, with some days showing a coherent band of strong profiler reflectivity throughout the afternoon and others having no discernible pattern at all.

We found that the decay of the CBL during the afternoon failed to show a single characteristic shape. From the wide range of behaviors, we identified two distinct patterns or categories. The descent category was identified as having strong reflectivity, decreasing in depth throughout the afternoon. It was found to be characterized by warm, moist conditions with weak turbulence and a weak capping inversion. In the ILS category, a strong band of elevated reflectivity throughout the afternoon was observed. These days typically had strong convection and strong capping inversions, and they were cooler and drier than the descent days. Wind profiles, surface measurements, radiosonde profiles, and surface fluxes were examined in each of the categories. Further study would reveal whether these categories are useful and whether others can be determined.

The time at which the transition begins is generally assumed to be around an hour before sunset, but we found that start times could be much earlier. We estimated the time at which the transition began for each categorized day and found a wide range of start times, with the transition sometimes beginning early in the afternoon.

Two obvious parameters that would be expected to have a significant influence but were not determined to be important in our study are cloud cover and the synoptic situation. The overall cloud fraction was very sim-

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ilar in each category, and there was also at least one cloud-free day in each category. The descent days were found to have more cloud during the early afternoon than did the ILS days. The influence of synoptic-scale systems acting on the CBL, such as a high pressure center compressing the CBL in the descent case, also seems unlikely given that the pressure on these days was generally lower than in the ILS category.

Results from previous research coincide more closely with the observations of our ILS category than with the descent-category observations, which probably is due to the fact that the initial conditions considered in those studies are similar to those in the ILS category, with a well-mixed CBL and a strong capping inversion present during the afternoon. Grant (1997), Sorbjan (1997), Nieuwstadt and Brost (1986), André et al. (1978), and Kaimal (1976) all observed evidence of an elevated inversion persisting throughout the period of declining surface heat flux and a decrease in turbulence during the afternoon throughout the CBL but more rapidly near the top.

Nieuwstadt and Brost (1986) present a possible mechanism for maintaining temperature variations in the upper part of the CBL, as observed in the profiler reflectivity. They suggest that the strength of the temperature jump across the inversion is of critical importance to the persistence of temperature and velocity variations at the top of the CBL. With a moderate temperature jump, any air entrained by the still-active larger eddies would be warmer than that present in the mixed layer and would lead to large temperature variations. These variations would remain because the small-scale eddies that normally would distribute the entrained air would have decayed already. If the temperature jump is small (as in the descent category), then entrainment would bring down air very similar to that already present and the large gradients would not be created. With a large jump (as in the ILS category), entrainment would be negligible.

One possible explanation for the presence of the elevated band of high reflectivity in our ILS case may be that the capping inversion developed in this case is so strong that, even after becoming detached from the CBL and eroded during the afternoon, enough of a gradient still remains to produce the observed profiler reflectivity. In the descent case, the capping inversion is weak and is easily mixed away, even by the small wind shear present.

The behavior of the portion of the CBL remaining in contact with the surface may, in fact, be very similar in both categories, with the CBL beginning to decay earlier in the day in the descent case than in the ILS case simply because of the weaker turbulence conditions. This weakness could be due to the lower Bowen ratio, leading to more energy contributing to latent heat flux than to sensible heat flux and turbulence.

It would be useful to reproduce the different afternoon evolution patterns using a computer model, because this would allow us to remove the influence of humidity on the profiler sensitivity and to isolate the most important parameters driving the transition.

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