1.5 WATER VAPOR VARIATIONS IN ECHO PLUMES IN THE CONVECTIVE BOUNDARY LAYER

Bart Geerts[1] and Qun Miao
University of Wyoming

1. INTRODUCTION

The Wyoming Cloud Radar (WCR), a 95 GHz Doppler radar aboard the University of Wyoming King Air (UWKA), extensively sampled the optically-clear, quiescent convective boundary layer (CBL) during IHOP. The term 'quiescent' CBL indicates that the flight tracks avoided mesoscale convergence zones evident as well-defined singular radar fine-lines. Echo plumes evident in WCR reflectivity transects may be footprints of coherent circulations within the CBL. Most plumes extend throughout the CBL depth. Their width and spacing is variable (**Fig 1**). Observations from numerous flights indicate that they are absent at sunrise and grow in depth and spacing during the morning hours as the CBL establishes and deepens. They can be referred to as *bug plumes* because the WCR echo in the optically-clear warm-season CBL is largely due to small insects (Wilson et al 1994).

The UWKA carried a large array of probes to measure air motion, state variables, fluxes, and land surface characteristics (see http://flights.uwyo.edu/ihop02/ for details). Water vapor variations were measured by the rapid response Licor 6262 and Lyman Alpha probes.

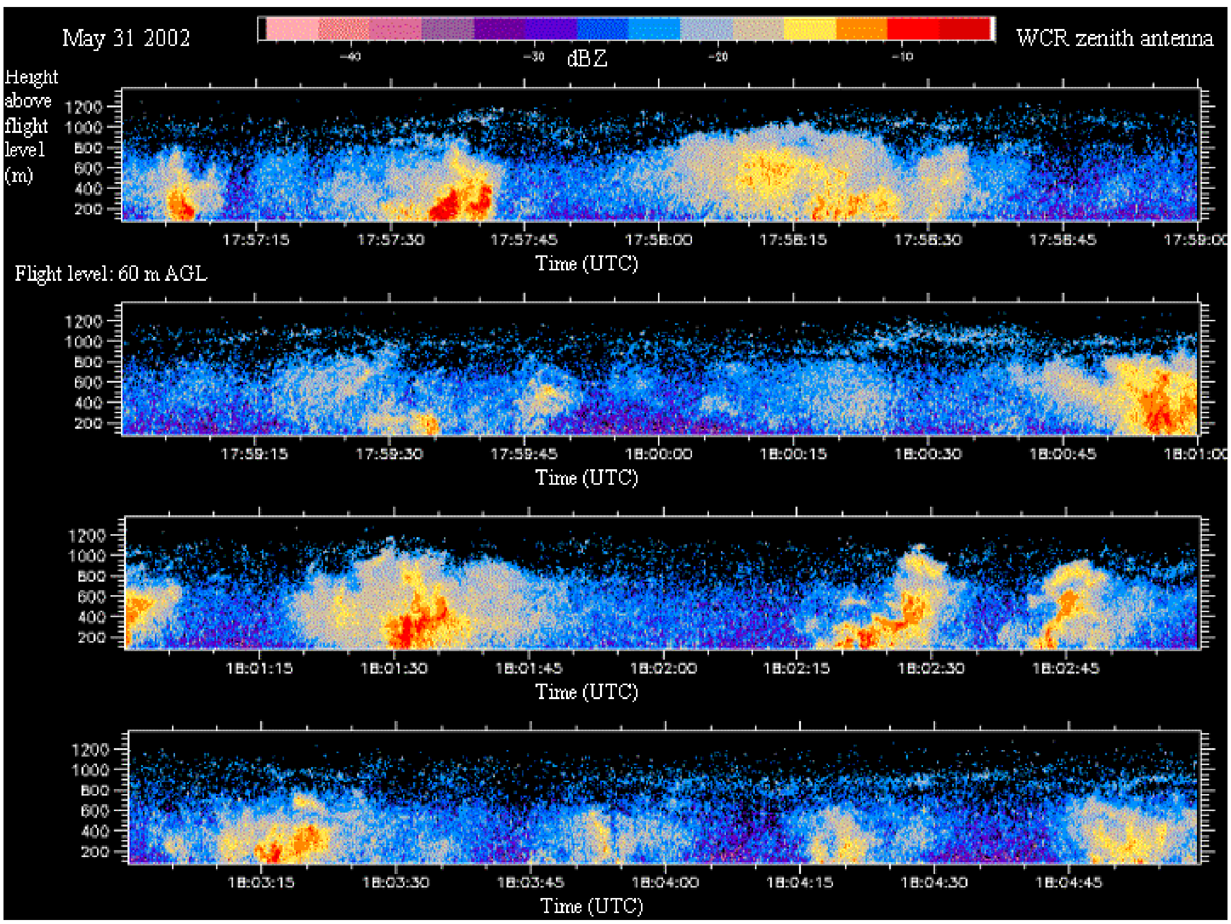

Fig 1. WCR zenith equivalent reflectivity on 31 May 2002 between 12:57-13:05 Central Daylight Time (CDT) in south-central Kansas. The aspect ratio of each panel is 1:1. The four panels cover a total distance of 38 km.

[1] *Corresponding author address*: Dr. Bart Geerts, Department of Atmospheric Sciences, University of Wyoming, Laramie WY 82071, USA; email: geerts@uwyo.edu

This study uses the extensive IHOP record of combined WCR/UWKA data with the following objectives:

- to document the vertical velocity structure of bug plumes, both at flight level and throughout the depth of the plumes;
- to demonstrate that bug plumes represent CBL thermals, i.e. that they tend to be buoyant or at least ascending;
- to show that bug plumes contain more water vapor than the interstitial CBL air, and that they are responsible for an upward moisture flux within the CBL;
- to assess dynamical and land-surface controls on the location and spacing of plumes.

2. RADAR OPERATIONS IN BLH MISSIONS

Some 34 hours of WCR data (or 10,000 km of flight track) were collected on Boundary Layer Heterogeneity (BLH) flights in IHOP (**Table 1**). BLH flights were designed to study the impact of surface heterogeneities on surface fluxes, especially water vapor fluxes, during the afternoon when the CBL is best developed and rather steady. Pre-selected tracks were frequented at flight levels ranging from 1.2 Z_i (Z_i is the CBL depth) to 60 m above ground level. Three tracks were used during IHOP, one in the Oklahoma Panhandle ('western' in Table 1), one near Wichita in Kansas ('central'), and over the Walnut Creek watershed in Kansas ('eastern'). In addition, some 16 hours of WCR data were collected in Boundary Layer Evolution (BLE) flights near the western track. BLE flights were conducted between sunrise and early afternoon.

The WCR operated in three possible antenna modes during these flights (Table 1). The UD (up/down) mode, where the nadir and zenith antennas operated simultaneously, was generally used at flight levels between 0.3-0.8 Z_i. In this mode the flight-level data can be combined with the WCR echo and vertical velocity profiles, which are continuous except within 100 m from the flight level. On most flight legs the UWKA flew around 60 m above ground level, with the WCR looking upward only (UP) out to a maximum range of 2250 m. At least one flight leg on each flight employed the Vertical Plane Dual-Doppler (VPDD) mode while flying just above the CBL. Here radial velocities from the nadir antenna and from the slant antenna (30° forward from nadir) can be synthesized to obtain the air flow (u,w) in sections below the aircraft track (Leon et al 1999).

The nadir antenna is the most sensitive, on account of the use of low-loss waveguides and the antenna size (46 cm diameter, as opposed to 38 cm for the slant antenna and 30 cm for the up antenna). Its minimum detectable signal at a range of 1 km is about –35 dB, as opposed to –31 dB for the up antenna, assuming a pulse width of 250 ns and an average of 500 pulses. All antennas have beamwidths less than 1°. For the pulse width of 250 ns, which was used on all BLH flights, the range resolution is 36.5 m, and the along-track resolution about 4 m. More details about the WCR can be found at http://www-das.uwyo.edu/wcr/.

Because the flight legs repeatedly covered the same straight track, WCR data have been redistributed to a geographically fixed Cartesian grid with horizontal and vertical resolutions of 30 m. The gridded echo and vertical velocity data allow us to assess:

- how the vertical structure of bug plumes varies, in terms of vertical motion and echo strength;
- how plumes evolve and/or are advected, over time periods ranging 3 to 30 minutes;
- whether a geographical preference exists for plumes.

The latter can be related to surface topography or land surface characteristics, as measured by UWKA probes measuring the albedo, the surface skin temperature, and the normalized differential vegetation index (NDVI), as well as flux stations on the ground.

3. PLUME VERTICAL VELOCITY STRUCTURE

The WCR-derived zenith-beam vertical velocity, corrected for aircraft motion, is shown in **Fig 2** for some of the plumes shown in Fig 1. Plumes are generally ascending, and stronger plumes tend to have higher peak ascent rates, however the width of updraft cores tends to be smaller than that of the echo plumes, and some areas of moderate echo strength experience subsidence (e.g. at 18:01:40 UTC). The echo strength in inter-plume regions generally is too low to estimate vertical motion.

date	UWKA data	CBL depth (m)	track	WCR times (UTC)	WCR operating modes	WCR echo strength	comments	Coordination with			
								P-3	Falcon	MIPS	DOW
5/19	all OK	1100-1500	western	16:47-00:39	UP(6), UD(2),VPDD(2)	good	clear weather, strong inversion, relatively deep and active ABL	+	+	+	-
5/21	all OK	1500	central	18:33-21:02	UP(6),VPDD(2)	very good	scattered cumulus with scattered cirrus above, hazy, many bugs on the windshield	+	+	-	-
5/25	all OK	1800	western	16:46-20:21	UP(10),UD(2), VPDD(1)	good	no low cloud, scattered variable broken cirrus, shallow CBL after cold-frontal passage, interesting moisture distribution	-	+	+	-
5/27	all OK	600-800	eastern	15:57-18:41	UP(7),UD(7)	OK	very green surface, high cirrus or cirrostratus, scattered altocumulus	+	-	-	-
5/29	all OK	800-1500	western	16:31-22:09	UP(5),UD(8), VPDD(5)	very good	a strong horizontal gradient in soil moisture caused by rainfall in past 1-2 days	+	+	-	+
5/30	all OK	500-1000	eastern	16:37-19:53	VPDD(2),UD(6), UP(7)	OK	scattered cirrus, a few forced cumulus clouds, a distinct haze layer	-	-	-	-
5/31	all OK	1200-1300	central	17:51-20:16	UP(7),UD(3)	very good	skies almost clear, with a patch or two of cirrus, two very good cases for up beam	-	+ HRDL	-	-
6/6	Heiman dead	800-1600	central	16:53-22:58	UP(3),VPDD(3), UD(6)	good	virtually clear, a few small cumulus, cirrus to the south, significant haze near the top of the BL; BL well mixed through the end	-	+ HRDL	-	-
6/7	Heiman incorrect	800-1000	western	16:33-19:59	UP(7),UD(6)	weak	low mixing ratio, BL depth varied considerably	+	+	+	+
6/16	all OK	800-900	central	17:03-21:54	UP(8),UD(4)	OK	not very turbulent, standing water in fields after recent rain	+	-	-	-
6/17	all OK	1600-1800	eastern	16:37-20:28	UD(12),UP(6)	OK	scattered, thin cumulus humulis with some very scattered altostratus, altocumulus, and cirrus toward the end of the mission	-	-	-	-
6/20	all OK	1100-1500	eastern	16:31-20:36	UD(11),UP(5)	weak	scattered cumulus humulis, scattered thin cirrus, slight static stability	-	-	-	-
6/22	all OK	1200-1600	eastern	17:03-19:29	UP(10),UD(8)	weak	clear conditions with some scattered cumulus, hazy at upper levels	+	-	-	-

Table 1. Summary of Wyoming Cloud Radar (WCR) and Wyoming King Air (UWKA) data collected on Boundary-Layer Heterogeneity (BLH) missions during IHOP. The CBL depth is estimated from aircraft soundings. The operating modes are discussed in the text. The qualification of WCR echo strength is subjective; ‘very good’ implies that the CBL is generally sufficiently filled with echoes to estimate radial velocities in between bug plumes, while ‘weak’ means that the echo strength of the entire CBL, except the major plumes, is below the WCR sensitivity threshold. The last four columns list other IHOP platforms: the NRL P-3 (with ELDORA), the DLR Falcon (with the High Resolution Doppler Lidar, HRDL), MIPS (mobile integrated profiling system) and DOW (Doppler on Wheels).

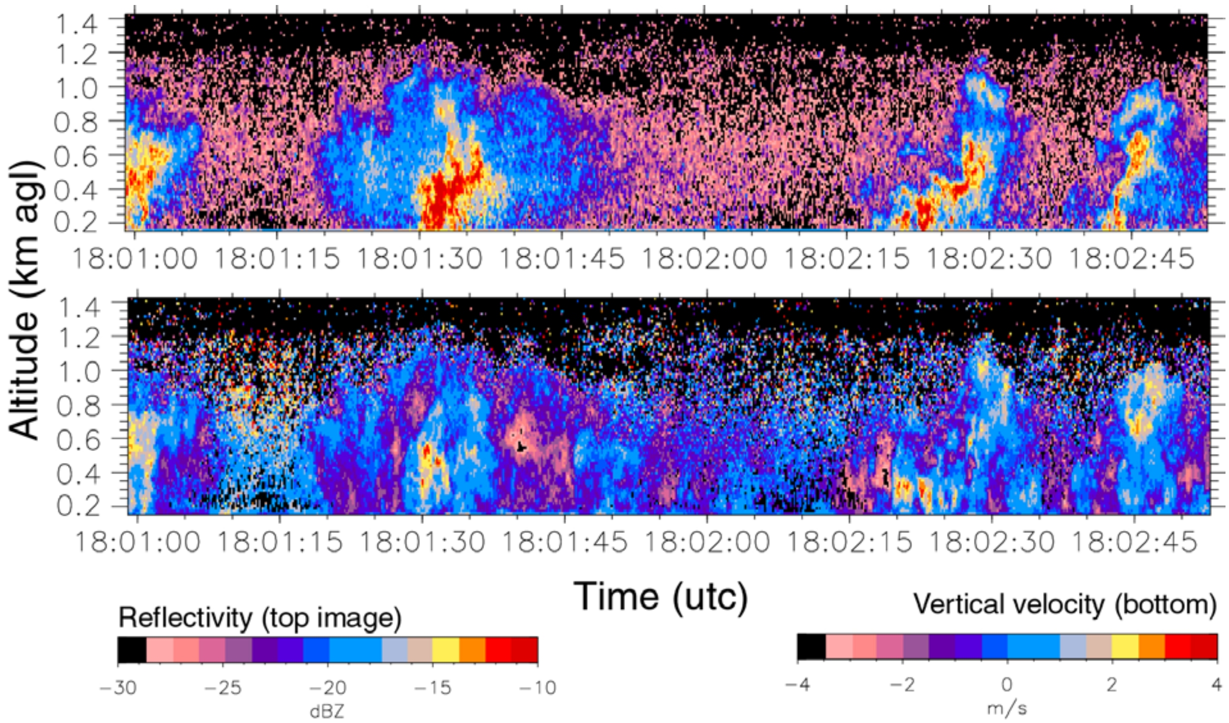

Fig 2. WCR reflectivity and vertical velocity profile corresponding to a section of the flight leg shown in Fig 1, between 18:01 – 18:03 UTC. The aspect ratio is 2.5:1.

The WCR vertical velocity field may be contaminated to some degree by the fallspeeds of the scatterers. The large concentration of scatterers in plumes, evident by a plume reflectivity of at least 20 dB above background values, suggests that insects actively oppose updrafts in which they become embedded. Because the WCR echo is likely mostly due to small insects, this bias should be less than 1 ms^{-1}. Our presentation will validate the WCR measured vertical velocity against that measured by the gust-probe onboard the aircraft, both by comparing the WCR velocities closest to the aircraft (above and below) as well as making a statistical comparison at different altitudes within the BL.

If the bias is insignificant, or if we are able to establish a correction of vertical velocities for the fallspeed of the scatterers, then we plan to conduct a systematic analysis of the approximately 34 flight hours during IHOP in the quiescent convective BL to establish:

(a) whether echo plumes tend to correspond with updrafts;
(b) whether echo plumes are thermals, ie whether they have positively buoyant bases or cores;
(c) whether WCR-resolved echo plumes converge low-level moisture and realize an upward moisture flux in the convective BL;
(d) whether echo plumes in the quiescent BL are tied to variations in land surface conditions or whether they reflect BL dynamics that are independent of land surface conditions.

To address (d) we will use aircraft-based land surface characterizations (albedo, NDVI and skin temperature), and aircraft-based soundings conducted at regular intervals. Also, land-surface forcing implies that plumes are locked to or at least triggered by surface features. During the BL flights the same flight tracks were repeated at different altitudes – thus, we should be able to assess if certain surface features are associated with plumes more often than others.

To examine the vertical structure of plumes and their ascent rate, we display a frequency-by-altitude diagram (FAD) of reflectivities and vertical velocities (**Fig 3**). These FADs show the ‘normalized’ probability of encountering a given value bin at a given height. It is normalized in the sense that the integral of all probabilities, over all values and all levels, equals 100. This is different from the contoured FADs (CFADs) in Yuter and Houze (1995), who normalize the distributions by the number of points *at each level*. A division by all numbers of points (all values, all levels) has the advantages that it shows the relative occurrence of values at different levels, and that the probabilities do not converge to 100% at the echo top of the deepest plume. The level of most rapid decay of reflectivity with height is a measure of the average depth of the CBL. Also, the smaller the reflectivity gradient and the larger the vertical velocity range are near the CBL top, the larger is the topographic variability of the BL top.

The FAD for the section shown in Fig 1 shows that echoes disappear around 1300 m AGL (Fig 3), which is about 200 m higher than Z_i derived from aircraft soundings nearby. A true reflectivity decay at the CBL top is not found, because the echo noise increases with square of the radar range. The large velocity variations above the CBL suggest that the remaining echo there is noise.

Both the mean reflectivity and its standard deviation tend to decay with height *within* the CBL (Fig 3). This may imply that the echo source region is near the surface, and that echoes are dispersed near the tops of plumes. Echoes tend to rise at ~1 m s^{-1} at low levels, while the mean vertical velocity in near zero at the CBL top. However the spread is rather large, and a significant fraction of the plumes is subsident. Strong plumes (those with reflectivity exceeding –25 dBZ, as shown in Fig 3, or higher thresholds) do not show a tendency to be ascending faster, in other words the plume strength is not a measure of its updraft speed.

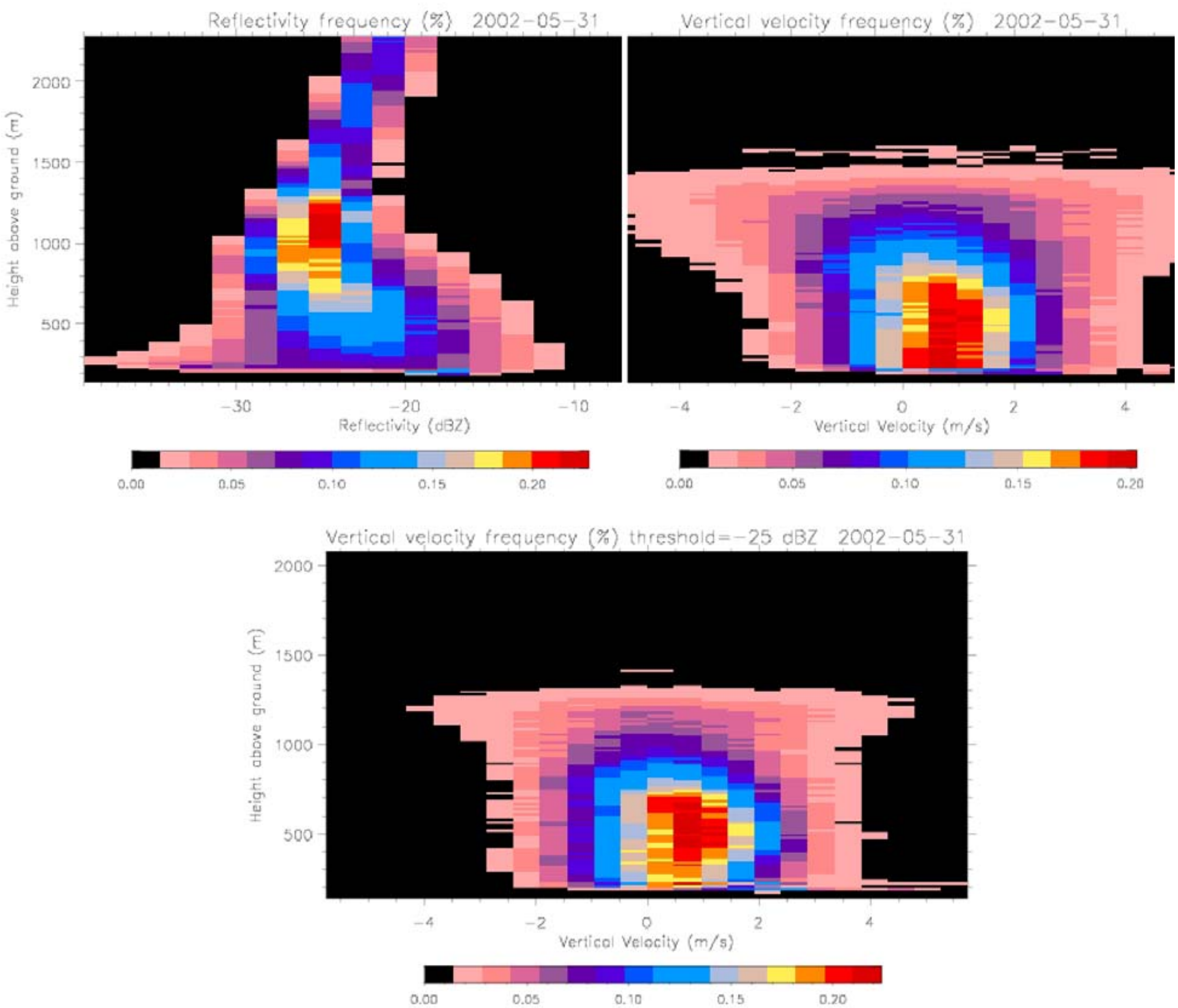

Fig 3. A frequency-by-altitude diagram (FAD) of WCR reflectivity (upper left) and vertical velocity (upper right) for the flight leg shown in Fig 1. Also shown, below, is a vertical velocity FAD counting only pixels whose reflectivity exceeds –25 dB.

4. BUG PLUMES AND THERMALS

The 38 km transect shown in Fig 1 contains several irregularly-spaced bug plumes in a quiescent CBL. The plumes have a peak reflectivity at least 25 dB higher than the background reflectivity between plumes. Here the 'background' generally falls below the detectibility threshold. An aircraft sounding just before this flight leg reveals a well-mixed BL, 1100 m deep, capped by a thin stable layer with a potential temperature increase ($\Delta\theta$) of 6 K and a mixing ratio decrease (Δq) from 11 to less than 4 g/kg. The wind shear across the BL top was about 8 m s^{-1} km^{-1} from 200°, i.e. almost normal to this east-west oriented transect. Most plumes reach the top of the BL and do not appear sheared in the cross section.

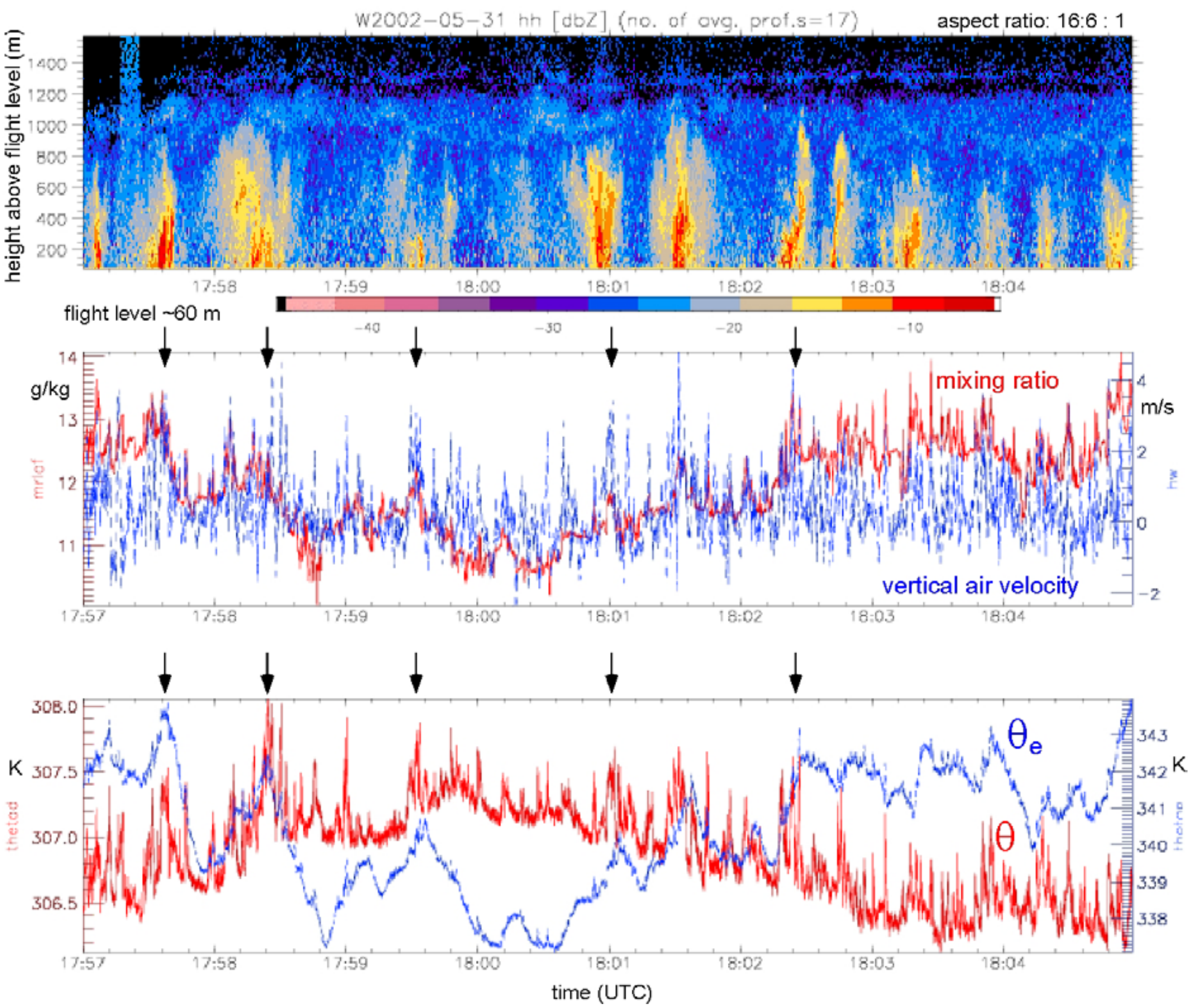

Fig 4. (top panel) WCR reflectivity profile corresponding to Fig 1, displayed at an aspect ratio of 16.6:1; (middle panel) flight-level data below the WCR transect, with mixing ratio (g/kg) in red and vertical air velocity (m/s) in blue; (bottom panel) ibidem, but (equivalent) potential temperature in (blue) red. The black arrows highlight some echo plumes associated with positive anomalies in the flight-level variables shown below. The WCR echo spike at 17:57:20 UTC is due to VHF radio interference.

On this flight leg echo plumes appear to be positively correlated with moisture anomalies below, i.e. at the flight level of 60 m (**Fig 4**). The plumes also tend to have a base that is warmer than the surrounding environment and is ascending, although these correlations are less obvious. The plume-scale anomalies are superimposed on larger-scale moisture variations. A 10 km wide zone (between 17:58:40 and 18:00:40 UTC) is rather devoid of echoes. This zone also has a 1-2 g kg^{-1} lower mixing ratio yet a 0.5-1 K higher potential temperature than the surrounding area, suggestive of either subsidence or drier land surface conditions. Variations both on the larger and smaller scales may be associated with BL circulations, which may be controlled either by ambient wind shear/stability, or by land surface variations.

The thin layer of weak echo above the plumes in Fig 2 corresponds with the height of the BL top. On many occasions such layer is absent, but sometimes it is obvious, in fact in at least one case (May 29 16:40 UTC) the echo layer marking the BL top had an echo strength comparable to that of the plumes. This occasion was marked by moist land surface conditions and a strongly-capped mixed layer. The nature of these capping echoes is unclear, but it is very unlikely that they are due to Bragg scattering.

5. DISCUSSION

The plume buoyancy-moisture correlations evident in Fig 4 and the probability density functions in Fig 3 are based only on 8 minutes of flight. All UD and UP WCR profiles will be merged with flight-level data to document the echo and vertical velocity structure of bug plumes, and to assess whether they are positively buoyant at various levels within the CBL. If these plumes do indeed manifest thermals in various stages of evolution, then the morphology, spacing, evolution and vertical velocity structure of the plumes should prove to be invaluable to large eddy simulations of the CBL over heterogeneous terrain.

The key question, to be addressed at the Symposium, relates to the moisture anomalies in thermals. Flight-level data will be used to assess such anomaly and to estimate the flight-level water vapor flux. Large differences may be found regionally and on different days. A water vapor flux profile can further be derived, assuming the conservation of mixing ratio in plumes of known vertical motion. Such flux profile will only capture the upward transfer, as echoes are generally too weak between plumes to estimate the rate of subsidence there.

We further aim to delve into the dynamical interpretation of echo plumes in the quiescent CBL. The plumes may reflect variations in land surface conditions or topography, or else they may reflect inherently atmospheric BL dynamics. To address this we will examine stationarity and use aircraft-based land surface characterizations (albedo, NDVI, and skin temperature), and aircraft-based soundings, which were conducted at regular intervals.

6. CONCLUSION

A wealth of high-resolution radar reflectivity and radial velocity profiles of the optically-clear, undisturbed convective boundary-layer have been collected during IHOP. The BL is marked by echo plumes, which generally penetrate to the BL top. A preliminary analysis suggests that these plumes correspond with thermals of ascending, anomalously moist air. A more comprehensive analysis will be presented at the Symposium.

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