12A.4 VERTICAL VELOCITY AND BUOYANCY CHARACTERISTICS OF ECHO PLUMES DETECTED BY AN AIRBORNE MM-WAVE RADAR IN THE CONVECTIVE BOUNDARY LAYER

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1. INTRODUCTION

One outstanding puzzle in wind profiler data is the tendency for vertical motions to be negative over flat terrain, especially in the convective boundary-layer (CBL)(Angevine 1997). Erroneous velocities on the order of 20-40 cm s^{-1} are reported during the daytime and they virtually disappear at night. After eliminating various sources of possible measurement error, Angevine (1997) concludes with the speculation that the errors are due to small targets (particulate scatterers detected by 915 MHz radar) that have a systematic downward velocity.

In this study vertical velocities in the CBL are studied at much higher resolution, by means of an airborne 95 GHz (3 mm) Doppler radar, with as objectives to confirm this downward bias and to interpret it in terms of insect behavior and CBL dynamics. In comparison with 915 MHz radar data, 95 GHz radar profiles can be sampled at higher frequency, and the 95 GHz signal is not affected by Bragg scattering. The benefit of airborne measurements, compared to ground-based radar profiles, is the availability of in situ thermodynamic and kinematic observations, and the direct observation of horizontal structure. Fixed profiling radars can do this indirectly, by converting time to distance, assuming some advection speed. Such procedure is questionable because the evolution time scale of thermals may be smaller than its advective time scale.

2. AIRBORNE W-BAND ECHOES AND RADIAL VELOCITIES IN THE CLEAR-AIR CONVECTIVE BOUNDARY LAYER

Reflectivities and Doppler velocities from the Wyoming Cloud Radar (WCR, http://www-das.uwyo.edu/wcr/) are used to describe the detailed (~25 m) vertical velocity and echo structure in the optically-clear convective boundary-layer (CBL). This study focuses on the quiescent CBL, i.e. away from mesoscale convergence zones such as fronts. Some 30 hours of combined radar and in situ aircraft data were collected in the undisturbed, mature CBL over the central Great Plains of North America in May-June 2002, as part of IHOP_02 (The International Water Vapor Project, Weckwerth et al 2003). The key radar configuration used for this study is the <u>profiling</u> mode, with fixed antennas looking up and down from the aircraft, the Wyoming King Air. The first reliable radar gates are 120 and 75-90 m from the aircraft, in the down and up direction respectively, so there is a ~200 m blind zone, within which high-rate in situ measurements are taken.

The detectability of coherent buoyant eddies in the clear CBL by means of an airborne 95 GHz radar came as a surprise during the IHOP campaign. Shallow radar 'fine-lines' in the clear air have long been described by means of operational scanning C or S-band radar data (e.g. Wilson and Schreiber 1997), and forecasters have come to monitor them in the warm season, because thunderstorms may be triggered along them. The flight tracks used here intentionally focused on the quiescent CBL, without major fine lines. Nevertheless much echo variability existed within the quiescent CBL. Echo plumes were encountered at irregular intervals. Their depth was about that of the CBL, and their strength about -10 dBZ.

What fraction of the CBL can be seen by the WCR? The radar sensitivity threshold is about -28 dBZ at a range of 1 km. On one spring day in the central Great Plains, some 72% of all CBL regions had at least half of their profiles sampling plumes (at least 200 m deep) whose reflectivity exceeded -25 dBZ, and 97% of the regions had at least half of their profiles sampling a -30 dBZ or stronger plume (**Fig 1**). The implication is that most of the CBL can be 'seen'.

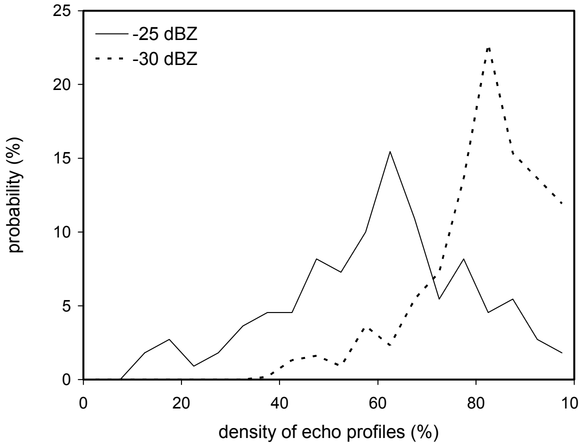

Fig 1. Histogram of the probability that echoes exceed -25 and -30 dBZ, over a continuous depth of at least 200 m within the clear-air CBL. The density of echo profiles is calculated during 1 min (~1800 profiles), and all samples were collected during 110 min on the afternoon of 5/29/02 on the Western track.

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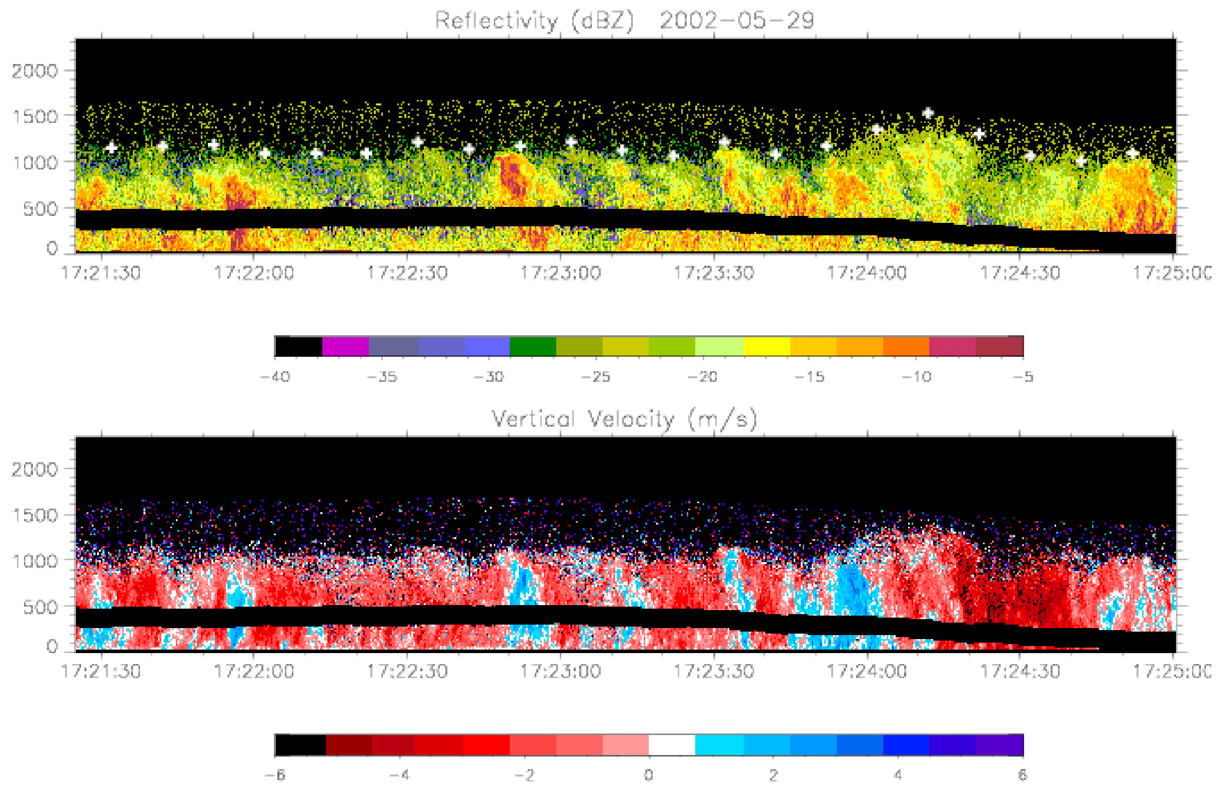

Fig 2. Example of radar reflectivities (top panel) and WCR vertical velocities (bottom panel) for part of a flight leg through the CBL. Vertical axis is height above ground level, horizontal axis is time (1 min = 5 km). White stars in the top panel indicate $\mathbf{z_i}$, determined based on the reflectivity gradient. The 200 m blind zone contains the aircraft track.

Echo “plumes” clearly mark the quiescent CBL. Above the CBL, the echo strength rapidly decreased, allowing objective determination of the CBL depth $\mathbf{z_i}$ (**Fig 2**). The CBL depth is defined as the level where the reflectivity and the signal-to-noise ratio both decrease rapidly. The CBL plumes generally contain updraft cores, yet the WCR data, from both the up and down antennas, indicate that subsidence prevails (red colors in the lower panel of Fig 2).

The vertical velocity shown in Fig 2 is derived from the WCR radial velocities, after careful removal of the components due to aircraft vertical motion and due to departures from the exact nadir and zenith orientations (Leon and Vali 1998). The latter departures cause a contamination of the aircraft ground velocity into the radial. A similar but much smaller contamination of this type occurs due to horizontal wind, and we attempted to correct for that as well.

A small systematic error in the nadir-beam vertical velocity can still exist, due to the off-nadir orientation of the nadir beam during flight. Such error does exist, and varies depending on aircraft fuel weight and speed. This error is removed, and the resulting bias should not exceed 10 cm s^{-1}. We verified this by computing the mean vertical motion of the ground, which should be zero. For the zenith beam, such validation is not possible, but the average nadir and zenith vertical velocities are within 10 cm s^{-1} of each other. For more details, see Geerts and Leon (2003) or Leon (2003).

3. VERTICAL VELOCITY BIAS

In IHOP we had the unique opportunity to compare radar-derived vertical motions to the ‘true’ vertical air motion. The latter, referred to as $\mathbf{w_a}$, is measured by the gust probe. After correction for aircraft motion by means of multiple GPS receivers, the air vertical velocity is derived with an accuracy of ~10 cm s^{-1} at a frequency that matches the WCR profiles (25 Hz). The WCR data obviously are displaced at a certain range from the aircraft, but the average value of the WCR vertical velocities at the nearest gate above and below the aircraft is centered within 20 m of the flight level. We refer to that up&down nearest-gate average as $\mathbf{w_r}$. The 200 m blind zone may be argued to be rather deep for linear interpolation, but vertical velocity cores can be seen to be continuous across this zone (Fig 2).

The difference between the two, $\mathbf{w_a} - \mathbf{w_r}$, is referred to as the vertical velocity bias. This bias has an uncertainty of about 20 cm s^{-1}, since the errors in both terms are largely independent. Such a bias, if it exists, can only be explained by the vertical motion of the targets, which are believed to be mostly small insects (Russell and Wilson 1997).

A preliminary comparison between $\mathbf{w_a}$ and $\mathbf{w_r}$ indicates that echoes tend to subside, at an average rate of 55 cm s^{-1}. The sign is consistent with vertical velocity averages documented by ground-based vertically-pointing radars at 0.915-2.5 GHz radars, although the magnitude is somewhat larger (Angevine 1997). The analysis is based on 78 minutes (about 400 km) of straight and level flight in the afternoon of 5/29/02 in the Oklahoma Panhandle. A more thorough analysis will be presented at the conference.

We now examine the variation of the radar vertical velocity bias with echo strength, vertical air motion, and altitude within the CBL. The sedimentation of echoes essentially is independent of echo strength (**Fig 3**). The strongest echoes tend to subside some 17 cm s^{-1} faster than the weak background echo, but the scatter is larger than the trend. The tendency for strong echoes to subside more is more obvious above 0.3 $\mathbf{z_i}$ (**Fig 4**), and the strongest echoes there tend to sink at about 1 m s^{-1}.

The rate of subsidence is however a clear function of the vertical air motion $\mathbf{w_a}$. For instance, in a 4 m s^{-1} updrafts the bias is 2.3 m s^{-1} on average, while at zero vertical air motion that bias is about 55 cm s^{-1}. A look at the scatter in Fig 3b reveals that in a downdraft, the bias is very small, and echoes seem to be subsiding at the same rate: the scatter is closer to the 1:1 fit line than to the linear regression. That is, insects actively oppose the updraft in which they are embedded. The opposition increases when the air rises faster, but it disappears in downdrafts, irrespective of its strength.

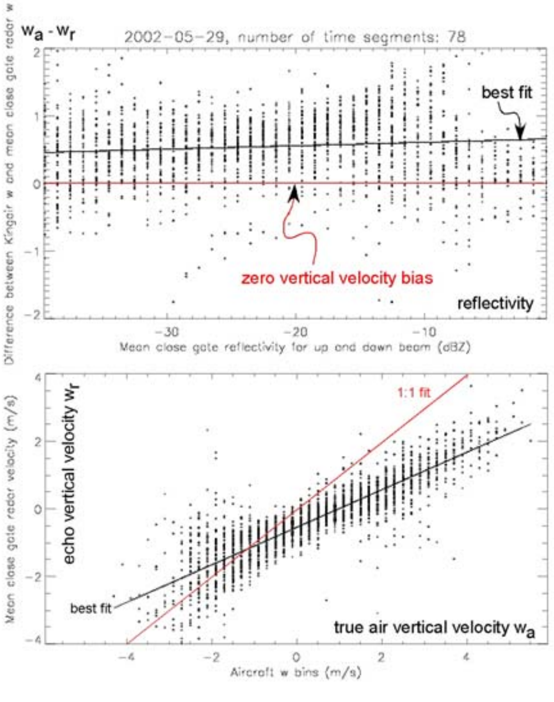

Fig 3. (top panel) WCR vertical velocity bias ($\mathbf{w_a}$–$\mathbf{w_r}$) as a function of echo strength, for 78 minutes of straight and level flight. Each dot represents a one-minute-mean bias value for a given reflectivity value (binned at 1 dBZ); (bottom panel) as the top panel, but here $\mathbf{w_r}$ is plotted vs $\mathbf{w_a}$, and $\mathbf{w_a}$ is binned in 0.2 m/s increments.

Measurements before and after dawn indicate that scatterers are almost absent in the stable nocturnal BL, but become prevalent again in the shallow CBL as it develops and deepens during the morning hours. This explains the absence of a vertical velocity error in nighttime wind profiler data (Angevine 1997): scatterers disappear at night and Bragg scattering, resulting from air turbulence, dominates. The latter is insignificant at 95 GHz, but it contributes to the daytime echo at 915 MHz, hence it is not surprising that the profilers' vertical velocity bias is smaller than the true rate of subsidence of insects lofted by BL thermals.

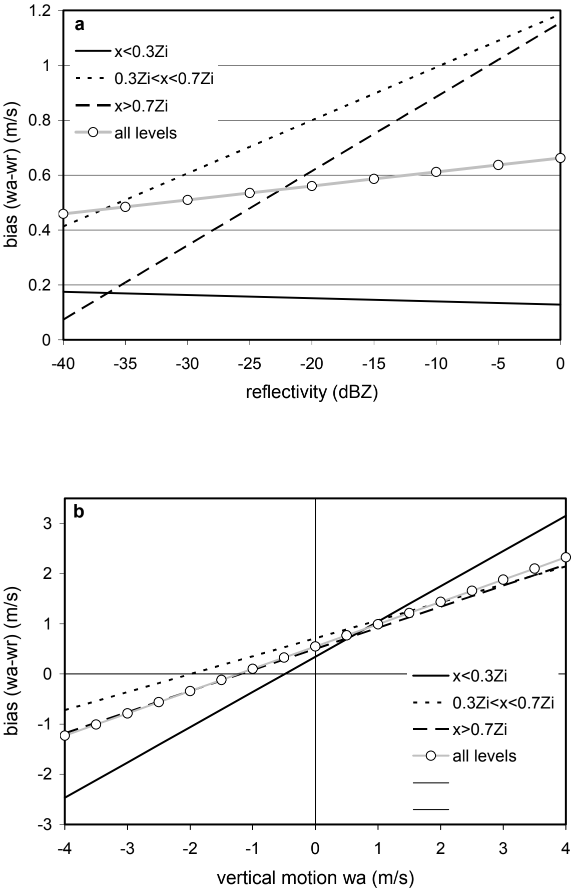

Fig 4. The variation of WCR vertical velocity bias ($\mathbf{w_a}$–$\mathbf{w_r}$) as a function of height within the CBL. Three flight levels are discerned, relatived to the CBL depth z_i. (a) dependence on echo strength, as Fig 3a. (b) dependence on vertical air motion, as in Fig 3b.

4. CONCLUSION

The downward bias documented in wind profiler data, especially in the daytime convective boundary layer (CBL) (Angevine 1997), has been confirmed by means of airborne radar and gust probe data. After careful correction of the radar radial velocity for aircraft motion, we find that *echoes in the undisturbed CBL tend to subside, at an average rate of 55 cm* s^{-1}. This rate of subsidence is larger than the uncertainty of gust probe and radar measurements. This figure is preliminary, based on one flight in the Oklahoma Panhandle. A more comprehensive analysis, based on several IHOP flights, will be presented at the conference.

We also confirm the correctness of Angevine's speculation about the cause of this bias, i.e. particulate scattering, most likely insects. the radar used in this study, the Wyoming Cloud Radar (WCR), is unaffected by Bragg scattering. The high temporal resolution of the WCR data reveals some patterns which can only be ascribed to the behavior of life insects: the rate of subsidence is largely independent of echo strength (this is not the case for dead scatterers like rain). And the echoes actively oppose the updraft in which they are embedded (whereas the fall speed of dead scatterers is independent of air vertical motion). The echoes subside rapidly in strong updrafts, but ride the downdrafts.

One obvious question yielded by these findings is why the CBL is filled with insects, at sufficient concentration to allow detection of most of the CBL, and to infer smooth Doppler velocity patterns at 30 m resolution (Geerts and Leon 2003). The answer is that thermals continuously pump and disperse insects into the CBL. These thermals are visible as echo plumes in the WCR transects (Fig 2). In terms of a prognostic equation for insect concentration, the source term is the eddy flux of insects, which is related to the eddy flux of heat that builds the CBL during the daytime. The sink term is the insect fall-out, which we find to be related to the eddy vertical motion.

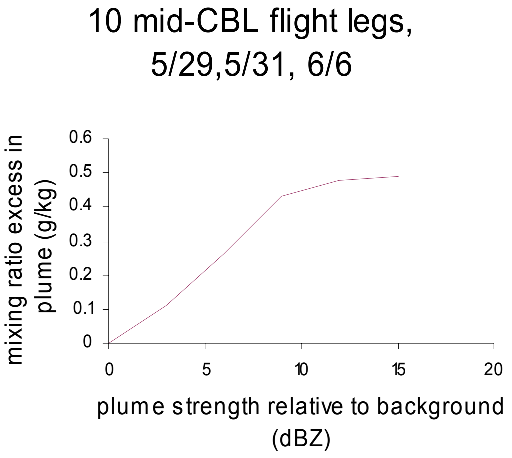

Fig 5. King-Air derived mixing ratio excess in echo plumes, detected by the nearest gates on the WCR up and down antennas. The plumes are defined in terms of their strength, which is measured as the up/down reflectivity average, as compared to that in the background.

In fact we see that on clear, calm mornings, the echo depth grows with the depth of the CBL, and that plumes grow in size accordingly (not shown). In the evening the eddy flux source term vanishes, and insects settle out, conceivably in less than one hour, given the average rate of subsidence. In fact we found in IHOP that nighttime and early morning WCR profiles were remarkably devoid of echoes, even in late spring.

We plan to further use the WCR data to describe these plumes and, more generally, the vertical velocities patterns in the CBL in more detail. In particular, at the conference we will show that the echo plumes tend to be buoyant, especially early on in their life cycle, and at low levels. And we will show that they also contain more water vapor (**Fig 5**), i.e. these plumes, as seen by the WCR, contribute to the upward transfer of water vapor through the CBL.

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