DYNAMICS OF THE CUMULUS CLOUD MARGIN: AN OBSERVATIONAL STUDY

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Abstract

Aircraft observations of shallow to moderately deep cumulus clouds are analyzed with the purpose to describe the typical horizontal structure of thermodynamic and kinematic parameters near the cumulus margin, from the cloud center into the ambient clear air. The cumuli were sampled in a broad range of environments in three regions: the tropical Atlantic Ocean in winter, the Sonoran Desert during the monsoon, and the arid high plains of Wyoming in summer. The composite analysis of 1624 cumulus penetrations shows that the vertical mass flux, temperature, buoyancy, the buoyancy flux, and the turbulent kinetic energy all tend to reach a minimum near the cloud edge. Most of these variables, and also the liquid water content, the droplet concentration, and the mean droplet size generally decrease in value from within the cumulus towards the cloud edge, slowly at first and rapidly within ~100 m of the cloud edge. These findings provide evidence for significant evaporative cooling in entraining and detraining eddies in the cloud margin. This cooling explains the tendency for downward accelerating, buoyantly driven subsidence in the cloud margin.

The tendency for a downward mass flux to occur in the cloud margin and in a thin shell of clear air around cumuli, and the apparent dynamical forcing of this flux are consistent with other recent observational and modeling studies.
1. Introduction

Cumulus clouds are important in the Earth system as they affect the vertical structure of tropospheric radiative heat flux divergence and dynamically couple the planetary boundary layer to the free troposphere through the vertical transport of heat, moisture, aerosol, and momentum (e.g., Siebesma et al. 2003). Cumulus cloud circulations are smaller than resolvable scales in numerical weather prediction (NWP) and general circulation models (e.g., Khairoutdinov et al. 2008), and they occur in a broad range of vertical and horizontal scales (e.g., Lopez 1977; Wielicki and Welch 1986). Cumulus clouds are the main source of precipitation at low latitudes and during the warm season at higher latitudes. It is largely because the sub-grid scale vertical transport by cumulus convection is inadequately presented in NWP models that precipitation is less predictable in the warm season than the cold season (e.g., Carbone et al. 2002; Weckwerth et al. 2004).

Many studies have examined macroscale geometric properties of cumulus clouds (e.g., Sengupta et al. 1990). These properties are in part controlled by the way in which cumuli exchange water and energy with their cloud-free environment. Entrainment of ambient air across the cloud edge fundamentally affects the cloud’s dynamics (e.g., Raga et al. 1990; Blyth 1993; Grabowski 1993; Krueger et al. 1997; Carpenter et al. 1998), and detrainment of cloudy air into the surrounding clear air cumulatively alters the environment. While lateral entrainment may affect the structure and evolution of organized cumulus convection, the focus of the present study is on the scale of individual cumulus towers.

The effect of turbulent mixing of cumuli with their immediate environment has been examined mainly by means of conserved-variable diagrams (e.g., Paluch 1979). While such diagrams are useful in the assessment of vertical and lateral entrainment, they do not describe the
characteristic horizontal structure of cloud properties from core to edge, nor the properties of the near-cloud environment. Many studies have displayed cloud edge thermodynamic data collected from individual aircraft penetrations of cumuli (e.g., Warner 1955), but single slices are not very meaningful in a turbulent environment. To our knowledge Rodts et al. (2003) were the first to composite aircraft data of kinematic, thermodynamic and cloud parameters from a large number of flight legs through cumuli and their immediate environment. A striking feature in their composites is a thin shell of descending air just outside the cloud edge. Rodts et al. (2003) attributed this local subsidence mainly to evaporative cooling resulting from mixing. Local subsidence in the cumulus shell, just ~200 m wide, had been noted before by Jonas (1990), using a smaller sample of aircraft penetrations. Jonas (1990) attributed this subsidence to mechanical forcing rather than evaporative cooling.

In this study we use aircraft data to examine the variation of vertical velocity, buoyancy, and cloud microphysical properties in the vicinity of the cumulus cloud edge, based on 1624 cumulus samples, both maritime on continental, in order to examine how entraining and detraining eddy fluxes affect the typical structure of cumulus cloud margins. In particular, we examine whether evaporative cooling in the cloud margin leads to a negative virtual potential temperature anomaly and sinking motion. The composite observations presented herein do not shed insight into the relative significance of vertical vs. lateral entrainment, but they do suggest a minimum dimension for buoyant cumuli to survive lateral erosion.

Data sources and analysis method are introduced in Section 2. Section 3 describes the characteristic horizontal structure of cumuli using a normalized distance, and stratifies this as a function of flight level in cloud. Section 4 re-examines the horizontal structure in terms of
physical distance from the cloud edge. And Section 5 (Discussion) revisits the key finding that cloud margin subsidence is driven by evaporative cooling.

2. **Data sources and analysis method**

A large number of cumulus clouds were penetrated by an instrumented aircraft, the University of Wyoming King Air (WKA), in four recent campaigns: a total of 95 hours were flown in two summertime campaigns in Wyoming, i.e. the 2003 **High-plains** Cumulus (HiCu-03) campaign (Damiani et al. 2006) and the 2008 Cloud-GPS campaign. These two datasets are collectively referred to as “High Plains”. The “Atlantic trade wind Cu” dataset is based on 89 flight hours targeting more shallow, precipitating cumuli over the tropical North Atlantic Ocean in the **Rain In Cumulus over the Ocean** (RICO-04) campaign, conducted east of the Lesser Antilles islands in winter (Rauber et al. 2007). And the “Arizona monsoon” cases are derived from WKA penetrations of shallow to deep orographic convection in Arizona in summer as part of the **Cumulus Photogrammetric, In-situ and Doppler Observations** (CuPIDO-06) campaign (Damiani et al. 2008; Geerts et al. 2008).

All flight data for the four campaigns were scanned for adequate samples of clouds and their immediate environment. The cloud selection criteria are based on the cloud droplet concentration $N_o$, obtained from the Forward Scattering Spectrometer Probe (FSSP). The FSSP count can, in theory, include ice crystals, but the ice crystal concentration is orders of magnitude smaller than the typical droplet concentration. The selection criteria are twofold: (a) the cloud (defined as a region with $N_o > 50$ cm$^{-3}$ in RICO-04, and $N_o > 100$ cm$^{-3}$ in the other campaigns) needs to be at least 400 m wide. And (b) no cloud can be present outside this cloud over a distance at least half the cloud width along the flight track.
The resulting 1624 Cu samples are characterized in terms of averages and distributions as a function of horizontal distance from the cloud center. We examine characteristics as a function of both the actual distance ($x$) across clouds (Section 4), and a normalized distance ($x^*$) (Section 3). The former gives an idea of the physical dimension of lateral exchanges across the cloud edge. The latter, a technique adapted from Rodts et al. (2003), allows an equal number of samples in each bin. In both cases, the transects are centered on the cloud edge. Thus $x^* = 0$ at the cloud edge; we set $x^* = -1$ at the cloud center. The composites shown only include data from the center of the cloud to a cloud half-width distance in the clear air, where $x^* = +1$. For some clouds this implies that two sections are included, the entry and exit parts. But for most clouds only one half can be included, because most sampled Cu towers occurred in clusters and the clear-air region between the towers was too small. All data are redistributed from a time dimension to a distance dimension at a resolution $\Delta x^* = 0.05$ using the air-relative aircraft speed.

In terms of flight direction, both cloud exits and cloud entrances are included. We have contrasted cloud exits against cloud entrances for a number of variables, in order to ensure that no measurement bias due to flight direction occurred. Temperature is measured by a reverse flow thermometer, an immersion probe developed to minimize in-cloud sensor wetting. The comparison between cloud entrance and cloud exit composite temperature traces shows that some wetting does occur, and thus also evaporative cooling following exit (Wang and Geerts 2009). The temperature has been corrected for this sensor evaporative cooling bias following Wang and Geerts (2009).

A fast-response water vapor sensor, the LICOR 6060, was available in only two of the four campaigns (RICO-04 and CuPIDO-06). This sensor displayed wetting symptoms in some cumulus penetrations, and there is evidence that at temperatures below 0°C rime sometimes
accumulated on the sensor, rendering the water vapor trace following cloud exit unreliable. This problem did not occur in RICO-04 (where penetrations were all below the freezing level), but the LICOR 6060 mixing ratio traces from RICO-04 still show a significant difference between the cloud exit and cloud entrance composites (Fig. 1). This difference is partly due to occasional instrument wetting, partly to an inadequate response time of the sensor, since there appears to be a lag of ~0.05 in the exit trace (Fig. 1). Both the evaporation of droplets and the slow instrument response are expected to produce a quasi-exponential adjustment to a step function change.

Because of the difference between exit and entrance regions, the LICOR 6060 data are not used in the composites. The other humidity sensor onboard the WKA, a chilled-mirror dewpoint sensor, was not used either because it has a much slower response time. Therefore the cumulus composites do not include humidity information. For derived variables dependent on humidity, such as buoyancy, we have to assume in-cloud saturation and essentially uniform conditions in the clear-air shell, as measured by the chilled-mirror dewpoint sensor. Under this assumption, traces of conserved variables such as total water and wet equivalent potential temperature (e.g., Paluch 1979) show an artificial discontinuity across the cloud edge. Therefore such otherwise useful variables are not shown.

Vertical and horizontal air velocities are derived from the WKA gust probe (Lenschow et al. 1991). The cloud liquid water content (LWC) is inferred from the FSSP, by integrating over all droplet size bins (Brenguier et al. 1994). This integration does not include drizzle or rain drops, but the FSSP LWC generally compares well (within ~10%) with that from the Gerber Particle Volume Monitor (PVM-100) (Gerber et al. 1994) and the DMT-100 (Droplet Measurement Technologies) hotwire probe (King et al. 1981) on the WKA. The mean droplet diameter ($D$) is also inferred from the FSSP.
The temperature, FSSP and the gust probe velocity measurements have a frequency of at least 10 Hz. The temperature sensor exhibits some lag to a step function temperature change, but it is shorter than 0.1 s (Spyers-Duran and Baumgardner 1983). For the smallest cloud in our sample (with a half-width of 200 m), \( \Delta x^* \) corresponds with 10 m or 8.5 Hz for a typical WKA flight speed of 85 m s\(^{-1}\). This implies that the data frequency is better than the resolution plotted in the normalized-distance composites for all 1624 Cu samples. In other words, any smooth or gradual transition of any variable across the cloud edge cannot be attributed to inadequate data sampling frequency or inadequate instrument response time.

For nearly half of the 1624 Cu samples in our data base, we were able to determine the cloud base and cloud top. The cloud base is defined as the lifting condensation level (LCL) (computed from a shallow mixed parcel near the surface) for those cases where soundings were available within ~two hours and within a distance of ~100 km. Numerous MGAUS (Mobile GPS Advanced Upper-air Sounding) radiosondes were launched during flight operations in RICO-04 and CuPIDO-06. Close-proximity soundings were not available for the High Plains Cu, so aircraft data just after take-off and/or just before landing were used to estimate the LCL. This LCL was compared against that inferred from temperature and dewpoint data from the nearest operational weather station, and the cloud base was chosen to be the lowest LCL.

The cloud top is defined as the highest echo seen by the Wyoming Cloud Radar (WCR) above the WKA during Cu penetration. This tends to be an underestimate (a) if the aircraft track is not right under the cloud top (e.g. for a tilted or cone-shaped Cu), and (b) if the cloud top echo is too weak for the WCR to “see”. The latter can be the case for shallow, ice-free continental Cu (weak echo) and for deep precipitating Cu (signal attenuation by interspersed precipitation). However a visual inspection of all cases reveals that the WCR reflectivity is rarely fully
attenuated near the top. Sometimes the echoes were too weak; then the case was eliminated. In some cases the cloud top appeared to be above the maximum range of the WCR data (e.g. 3 km above flight level). Even though the multi-antenna WCR was operational in all four campaigns, WCR zenith reflectivity profiles simply were not available for many Cu penetrations. The bottom line is that the cloud top could be estimated for 46% of all Cu samples.

3. Horizontal structure of cumuli and their clear-air shell

3.1 Basic cumulus characteristics

Histograms of the characteristics of the sampled cumulus clouds in the four campaigns are shown in Fig. 2. Clearly the High Plains cumuli were the most ‘continental’, with the highest $N_o$, the lowest LWC, and the smallest mean drop size. These Cu generally had a high cloud base, sometimes above the freezing level. Many Arizona monsoon Cu had a remarkably high LWC and, in terms of droplet size distribution and $N_o$, the Arizona monsoon Cu were intermediate between the maritime Atlantic trade wind Cu and the truly continental High Plains Cu. Most clouds contained some liquid or frozen precipitation, according to 2D-P (two-dimensional precipitation) particle probe and WCR data, with rain reaching the earth surface for most Atlantic trade wind Cu and for some Arizona monsoon Cu.

As will be shown below, most clouds in the three environments were cumuli congesti; cloud depths ranged from a few 100 m to ~6000 m. All Atlantic trade wind clouds were relatively shallow clouds with tops below the freezing level (Fig. 2d), while the Arizona monsoon Cu ranged in size from cumulus humilis to cumulonimbus. Almost all High Plains Cu and most Arizona monsoon Cu contained ice. There was a range of vertical velocities in the sampled Cu, implying that all stages in the life cycle of Cu towers were sampled. Most clouds
were rising, but a significant fraction of the Cu was sampled in their decaying phase with mainly sinking motion. The (orographic) Arizona monsoon Cu tended to have stronger updrafts and downdrafts than the Atlantic trade wind Cu (Fig. 2e). This is consistent with the higher convective available potential energy in MGAUS soundings released during the WKA flights in CuPIDO-06 (806 J kg\(^{-1}\) on average) than in RICO-04 (228 J kg\(^{-1}\) on average).

The rapid decay of Cu frequency with increasing size beyond the minimum half-cloud width of 200 m (Fig. 2f) is consistent with other studies of cumulus sizes (e.g., Lopez 1977; Wielicki and Welch 1986; Benner and Curry 1998). Some 92% of the Cu in the composite dataset was less than 2,000 m wide, yet some Cu were as wide as 6 km. The High Plains Cu tended to be the largest ones.

In short, the dataset of 1624 Cu penetrations represents mostly Cu congesti in a range of dimensions, Cu lifecycle stages, and ambient conditions.

### 3.2 Horizontal structure of cloud and dynamical variables

Frequency-by-distance plots of \(N_o\) and LWC are shown in Fig. 3a and Fig. 4a. Because there is a large range in mean values of mainly \(N_o\) and also LWC (Fig. 2a and b), these variables are normalized by their mean value between \(-1.0 < x^* < 0.0\) in Fig. 3a and Fig. 4a. Both variables vary significantly at all ranges from the cloud center. The normalization of \(N_o\) and LWC by the along-track mean brings out the remarkable along-track variability. Close to the cloud edge both variables approach zero. The mean values (shown as a bold line in Fig. 3a and Fig. 4a) indicate that both \(N_o\) and LWC decrease very slightly from the cloud center to \(x^* = -0.15\), and that they plummet from there to the cloud edge. The slow decrease of both variables, mainly between \(-0.50 < x^* < -0.10\), appears to occur in continental clouds only (Fig. 3c and Fig. 4c), and mainly in
updrafts, i.e. in younger clouds (Fig. 3d and Fig. 4d). The Atlantic trade wind Cu tend to have weaker updrafts (Fig. 2e) and a lower buoyancy flux (see below), and thus less turbulence near the cloud edge, and this may explain the lack of decrease in $N_o$ and LWC from the cloud center to $x^* = -0.10$.

More important is the rapid decrease in $N_o$ and LWC near the cloud edge, mainly between $-0.10 < x^* < -0.05$. The same applies to the mean droplet diameter (Fig. 5), which otherwise shows far less variability in individual Cu penetrations than $N_o$ and LWC (Fig. 5a). The remarkably uniform mean droplet diameter in cloud (within $x^* \leq -0.10$) is consistent with other studies (e.g., Paluch and Knight 1984).

The vertical velocity ($w$) composites (Fig. 6a) yield two findings that are not surprising: firstly, $w$ varies more in-cloud than in the clear-air shell: the standard deviation of $w$ at $x^* = -1.0$ is twice that at $x^* = +1.0$ (2.45 m s$^{-1}$ vs. 1.20 m s$^{-1}$). And secondly, updrafts (downdrafts) prevail in (out of) cloud, although nearly one third of the Cu were sampled in a late stage with downdrafts prevailing across the cloud (Fig. 6d). Two other findings are more surprising: firstly, the idea that vertical motion in the clear-air shell simply “compensates” the Cu vertical motion, i.e. that a stronger Cu updraft (downdraft) implies a stronger clear-air shell downdraft (updraft), that idea is wrong: in fact there is no significant correlation between mean $w$ [in-cloud] and mean $w$ [clear-air] (Fig. 7). As expected, most points in Fig. 7 fall in the upper left quadrant (cloud updraft, shell downdraft). We further expected most of the points in Fig. 7 to lie in an ellipse centered in the upper left quadrant, with the long axis pointing up (because the in-cloud drafts are larger than the clear-air shell drafts, Fig. 6), and tilted from the upper left to the lower right. But the stretching of the cloud of points from the lower left to the upper right in Fig. 7 suggests that the clear-air shell ($0.0 < x^* < +1.0$) tends to be dragged along somewhat with the cumulus
draft, especially in the Cu decaying phase. Thus compensating vertical motion must occur at some time lag and/or outside the clear-air shell ($x^* > +1.0$). Secondly, the clear-air shell does not respond uniformly. Air tends to sink more rapidly in the cloud margin ($-0.2 < x^* < +0.2$) than in the surrounding clear air, consistent with Jonker et al. (2008). This tendency even applies in old, subsiding clouds (Fig. 6d). The differential vertical velocity from Cu center to Cu edge is consistent with a toroidal ring circulation in cumulus towers (Damiani et al. 2006).

Assuming radial symmetry around the cloud center, the vertical mass transport $\dot{M}$ (kg s$^{-1}$) within a radius $R$ from the cloud center can be computed as $\dot{M} = \int_0^R \rho w 2\pi r dr$, where $\rho$ is air density and $r$ radius. Assuming lines of convection, the vertical mass flux would be $\dot{M} = \int_0^X L \rho w dx$, where $L$ is the length in the 3$^{rd}$ (along-band) dimension. The mean vertical mass transport for all Cu samples under these two assumptions is shown in Fig. 8. The more plausible radial symmetry assumption yields net upward mass transport within the clouds, but the ambient downward flux exceeds the in-cloud upward flux starting at $x^* = +0.40$, with a substantial net downward flux at $x^* = +1.0$. One would expect the integrated mass flux to be near zero at $x^* = +1.0$, or even slightly positive if some of the compensating subsidence occurs at a greater range from the cloud. The assumption of radial symmetry may offer some explanation. This assumption maximizes the area of the clear-air shell. In reality another cloud may be present within $x^* = +1.0$ in the off-track dimension, adding subsidence, or the cloud may be elongated in the off-track dimension. If the off-track cloud length is infinite (i.e., the “cloud band” assumption in Fig. 8), then the vertical mass flux remains positive out to $x^* = +1.0$. The apparent net downward mass flux over the Cu clear-air shell ensemble (Fig. 8) may be due in part to biased sampling: some 33% of the sampled Cu experience subsidence on average (Fig. 6d), and these
Cu may be overrepresented. In aircraft-based sampling such bias naturally results from the time lag between spotting a Cu target and penetrating it. This time lag is short, but not insignificant compared to the typical lifespan of a Cu tower.

Two observations arise from the mean perturbation “radial” velocity ($v_{rad}$) across the cloud edge (Fig. 9). Firstly, the radial velocity increases within cloud, out to about $x^* = -0.2$, especially in the more vigorous Arizona monsoon Cu (Fig. 9a). This suggests horizontal divergence, which is calculated in Fig. 9c assuming both radial symmetry ($\partial v_{rad}/\partial r = 1$) and banded clouds ($\partial v_{rad}/\partial x$). The prevailing divergent flow within the Cu core suggests that most of the sampled Cu were close to the equilibrium level on a thermodynamic diagram (i.e., the cloud top): horizontal divergence implies decreasing updraft strength, assuming incompressible air mass continuity. This is addressed further in Section 3.3 below.

The second observation brings us back to the localized subsidence at the cloud margin (Fig. 6a). The radial velocity decreases rapidly across the cloud margin (roughly $-0.2 < x^* < 0.2$) (Fig. 9a). This implies convergent flow within the cloud margin (Fig. 9c), especially in the upper cloud regions (Fig. 9d). Convergence implies that the cloud margin subsidence intensifies downward, and this suggests downward acceleration. The downward acceleration may be due to “compensating” forcing (i.e., the pressure perturbation acceleration induced by the Cu buoyant core). This forcing conceptually operates on a larger scale outside the cloud [e.g. Fig. 7.1 in Houze (1993)]. The downward acceleration may also be due to evaporative cooling both in entraining and in detraining eddies. This interpretation is consistent with the decrease in LWC near the cloud edge (Fig. 4) and with the negative temperature anomaly around the cloud edge (Fig. 10). It is also consistent with the fact that the LWC depletion (Fig. 4c), the cloud margin
downdraft (Fig. 6c), and the cool anomaly (Fig. 10c) are all more pronounced in continental clouds (with lower mean ambient relative humidity) than maritime clouds that formed in a more humid environment. And, finally, it is consistent with the LICOR 6060 water vapor increase towards the cloud edge due to detrainment (entrance trace in Fig. 1). Note that the entrance trace in Fig. 1 is unbiased (Section 2). This increase may be weak, but at least the near-cloud clear-air shell does not have the water vapor deficit that would be expected of simple compensating subsidence [see Fig. 6 in Rodts et al. (2003)].

We now examine whether the local cloud margin subsidence is buoyancy-driven. Buoyancy results not only from temperature anomalies, but is also affected by hydrometeor loading. We computed buoyancy (m s\(^{-2}\)) including all terms in the equation [e.g., eqn (2.51) in Houze (1993)] except the pressure perturbation term, which is ignored because the static air pressure is not known with enough precision:

\[
B = g \left[ \frac{\theta'}{\theta_o} + 0.61 q'_v - q'_H \right]
\]  

(1)

Here \(\theta\) is the potential temperature (K), \(q_v\) is the mixing ratio of water vapor (kg kg\(^{-1}\)), and \(q_H\) is the mixing ratio of liquid and/or frozen water (kg kg\(^{-1}\)). The parameters with a prime (‘\(\prime\)’) represent the deviation from the reference values, while the ones with subscript ‘\(o\)’ denote the reference states. Ideally the reference state would be represented by the far-field environment surrounding a cumulus cloud. Because other Cu were often present beyond \(x^* = 1.0\), we compute the reference temperature as the average value between \(-1.0 < x^* < 1.0\). Because of the very slow response of the chilled-mirror dewpoint sensor, the reference water vapor mixing ratio \(q_v\) is computed over the 500 m before the aircraft entered the cloud. The hydrometeor loading term \(q_H\) includes ice water, although in cold clouds (<-5°C) the ice water content was found to be an order of magnitude smaller than the LWC, on average, in the sample. As defined, the mean
buoyancy between $-1.0 < x^* < 1.0$ is not zero. Given the assumptions in the calculation of $B$, the sign of $B$ (positive or negative) is less meaningful than the value of $B$ at some point relative to its value in surrounding areas (Doswell and Markowski 2004).

Buoyancy patterns in and around Cu are shown in Fig. 11. The cool anomaly peaks at $x^* = -0.05$ (Fig. 10a), but the LWC there is much lower than deeper in cloud (Fig. 4a). Thus the negative temperature anomaly and the low hydrometeor loading largely compensate, resulting in no mean negative buoyancy at $x^* = -0.05$. Negative buoyancy does occur on average just outside the cloud, mainly at $x^* = +0.15$. The clear-air shell tends to be negatively buoyant relative to the cloud, and more so closer to the cloud edge. Inspection of Fig. 11d shows that this applies to rising Cu only; sinking Cu tend to be negatively buoyant relative to their immediate environment, as expected. On average the buoyancy flux\(^2\) is positive in-cloud (where positive buoyancy & updrafts dominate), near-zero in the cloud margin (where buoyancy is small) and more positive again in the clear-air shell (where negative buoyancy & downdrafts dominate), but there the buoyancy flux is only about half as large as in-cloud (Fig. 11a).

Thus turbulent kinetic energy (TKE) is generated [e.g., eqn (5.2.3) in Stull (1988)] mainly in-cloud, but also out of cloud. TKE is generated also by the shear in vertical velocity, between the cloud core updraft and the cloud margin subsidence. We computed TKE based on departures from the mean wind in the region $-1.0 < x^* < +1.0$ in three dimensions (Fig. 12). Typical TKE values are about three times larger in the middle of the Cu than in the clear-air shell, and they do not reach a minimum near the cloud edge. They are larger in the more vigorous Arizona

\(^2\) Note that the buoyancy flux is computed using perturbation quantities over the distance $-1.0 < x^* < 1.0$ only; the hydrometeor loading term is retained in the expression for buoyancy. In non-cloudy environments, the buoyancy flux is $\bar{w}'\theta_v'$, where $\theta_v$ is the virtual potential temperature and the overbar indicates a Reynolds average, but in cloud the hydrometeor loading term should be included. Also note that in this study the Reynolds average in the calculation of buoyancy flux and TKE applies to all cases in the composite, unlike the common method, in which averages in time or space are computed.
monsoon Cu than in the Atlantic trade wind Cu. In watching a towering Cu develop we may
assume that turbulence is contained and generated only within cloud. Clearly turbulence is
present and continuously generated also near the cloud edge and further in the clear-air shell.

Some of the results shown can only be explained by the flight strategies in the various
field campaigns. For instance, High Plains Cu and Arizona monsoon Cu were generally sampled
near the cloud top, often near a stable layer (i.e., the equilibrium level) where most clouds still
had much rising motion (Fig. 6c) but little buoyancy (Fig. 11c). A key objective in these
campaigns was to capture Cu convection with the dual-Doppler WCR antennas below the
aircraft. Aircraft penetrations through the upper half of the cloud show stronger divergent flow
within the Cu core (Fig. 9b and d), consistent with a flight level near the equilibrium level. Most
of the clouds in the campaigns in Arizona and Wyoming were rather deep or high, i.e. cold, and
this may explain the remarkable negative buoyancy of cold clouds (Fig. 11b): apparently some of
the cold Cu towers were overshooting (Fig. 10b). Clearly more can be learned if we can stratify
the horizontal structure statistics by cloud-relative flight level.

3.3 Cloud depth and flight level

The subset of Cu with cloud top and base information (Section 2) display a bimodal
distribution, with Atlantic trade wind Cu all with a cloud base below 1000 m MSL and a cloud
top below the freezing level, while other Cu have a much higher cloud base and generally peak
above the freezing level (Fig. 13a). Yet the cloud depth distribution has a single peak: most
clouds in the sample are about 2,000 m deep, some are as deep as 6,000 m. The Atlantic trade
wind Cu are the most shallow on average, and the High Plains Cu the deepest. Nearly half (43%)
of all cloud penetrations were in the upper quarter of the cloud, i.e. above a normalized height of
0.75 (Fig. 13b). Only a quarter of all cloud penetrations were in the lower half of the cloud. The cloud penetration level distribution was most uniform for the Atlantic trade wind Cu and most biased towards cloud tops for the High Plains Cu.

We used this Cu depth information to contrast “deep” Cu against “shallow” Cu, with a threshold depth corresponding with a 50-50 split in each of the three environments. This threshold depth is 1473 m for the Atlantic trade wind Cu, 1999 m for the Arizona monsoon Cu, and 2795 m for the High Plains Cu. Deep Cu tend to have more liquid water and a weaker warm anomaly, and therefore they are less buoyant than shallow Cu; but the updraft strength and vertical buoyancy flux are about the same (not shown).

Larger differences emerge from a contrast between lower- vs. upper-cloud level penetrations (Fig. 14). The upper-cloud penetrations encounter much more liquid water, as can be expected from moist-adiabatic ascent. The horizontal variation of LWC near the cloud edge (discussed in Section 3.2) is unaffected by flight level. The upper-cloud penetrations include both strongly buoyant cores and negatively-buoyant (overshooting) towers, and both strong updrafts and strong downdrafts (note the large standard deviations for upper-half penetrations in Fig. 14c, d, and e). The lower-cloud penetrations see much less variation in buoyancy and vertical velocity. Both buoyant updrafts and negatively-buoyant collapsing towers contribute to a large buoyancy flux in the upper regions of the cloud (Fig. 14f), and as result, TKE generation by the buoyancy flux is much larger there (not shown).

Three observations give evidence for the concept of a cloud top toroidal ring which contains the least diluted air (Blyth 1993; Carpenter et al. 1998; Damiani et al. 2006). The first two regard the kinematics, the last relates to the dynamics. Firstly, at upper levels in a Cu the updraft peaks near the center and becomes negative in the cloud margin (implying much
horizontal vorticity), while at lower levels the updraft is weaker, and more uniform within cloud (Fig. 14d). Near the cloud top the toroidal ring appears to merge with a broader circulation that includes subsidence in the clear-air shell. Secondly, at upper levels (more so than at lower levels) the horizontal flow is divergent in the Cu core and convergent in the cloud margin (Fig. 9d). And thirdly, the upper-cloud data suggest that the warmest, most buoyant part of the cloud is not the center (as it is in the lower half of the cloud) but rather near $x^* = -0.5$ (Fig. 14c and e).

4 Horizontal cloud structure in physical space

To address the question over what width liquid water becomes depleted near the cloud edge and a temperature deficit and subsidence occur in the Cu cloud margin, we map the composites shown above in physical rather than normalized space (Fig. 15). There is no reason to expect this width to scale with cloud diameter (Jonker et al. 2008). The drawback of this approach is that the sample size decreases rapidly with distance from the cloud edge (past the minimum half-cloud width of 200 m), but statistical significance can be judged by considering that sample size, shown as a dotted line in Fig. 15. Both $N_o$ (Fig. 15a) and LWC (Fig. 15b) decrease steadily from about $x = -700$ m to the cloud edge, thus the typical lateral entrainment depth of eddies (before they mix at fine scales with cloud air) is less than 700 m. The TKE is maximum in-cloud and also decays steadily towards cloud edge starting at roughly 700 m (Fig. 15f). The mean updraft strength (Fig. 15d) weakens from about the same distance towards the cloud edge, where downdrafts prevail. This is consistent with the results in normalized space (Fig. 6), with one difference that downdrafts only prevail partly out of cloud ($0 < x < 700$ m), and then updrafts dominate ($x > 700$ m, where the sample size becomes very small), while downdrafts prevail all the way out of cloud in normalized space. More important is the observation that
downdrafts prevail near the cloud edge, between about 70 m in-cloud and a few 100 m outside of cloud, peaking at about -0.7 ms\(^{-1}\) precisely at the cloud edge. The width and magnitude of this downdraft is roughly consistent with measurements documented in Heus et al. (2008) and Jonker et al. (2008).

A dynamical relationship is suggested by the matching asymmetric shape of subsidence (Fig. 15d), cold anomaly (Fig. 15c), and buoyancy (Fig. 15e) within the cloud margin (say -200 m < \(x\) < 200 m). These values decline rapidly between -100 m < \(x\) < 0, and recover more slowly in the clear-air shell. The cloud margin (specifically between -50 m < \(x\) < 100 m) is also the region of strongest horizontal convergence, which peaks precisely at the cloud edge (not shown).

Convergence implies local downward acceleration of the downdraft (\(\frac{\partial w}{\partial z} > 0\)) thus negative advection (\(w\frac{\partial w}{\partial z} < 0\)) and negative forcing following the parcel subsiding in the cloud margin (total derivative \(\frac{Dw}{Dt} < 0\)). Downward forcing is suggested by the cold spike (Fig. 15c), but buoyancy is only weakly negative in the cloud margin, with a positive spike near the cloud edge (at \(x\) = -10 m) on account of the sudden disappearance of liquid water (Fig. 15b).

The widest clouds sampled tend not to harbor a positive temperature anomaly, and with significant water loading their core buoyancy tends to be negative. This is interpreted as a sampling bias towards older clouds spreading out near the equilibrium level.

5 Discussion: cloud margin subsidence and evaporative cooling

Our sample of 1624 Cu penetrations is not unbiased, in particular in terms of flight level and cloud age, but it is the most detailed database to date for the study of the characteristic horizontal structure of Cu. The main finding regards the sinking motion in the cloud margin
(roughly -0.2< x* <+0.2, or roughly -200m <x< 200m). This air current appears to be anomalously cool and appears to accelerate downward. Except for a positive spike just inside the cloud edge, the cloud margin air is negatively buoyant compared to the surrounding air in the Cu core and the clear-air shell. This observation suggests that entraining eddies driven by the convective circulation mix environmental air more effectively in the margin of cumulus clouds than deep into the cloud core. Turbulent mixing tends to deform volumes of entrained air into thinner, smaller filaments until the Kolmogorov scale is reached. Much of this mixing appears to be accomplished before the Cu core is reached.

As further evidence for the hypothesis that evaporative cooling in the cloud margin drives subsidence, we divide the entire sample in two classes depending on ambient humidity (Fig. 16). Evaporative cooling is proportional to the vapor pressure deficit \( e - e_{\text{sat}}(T) \), where \( e \) is the ambient vapor pressure and \( e_{\text{sat}}(T) \) the saturation vapor pressure with respect to water at temperature \( T \) in cloud. For each penetration, \( e_{\text{sat}}(T) \) was calculated in cloud only (-1.0 <x*< 1.0), and \( e \) was derived from \( e = e_{\text{sat}}(T_d) \), where \( T_d \) is the average chilled-mirror dewpoint in the 500 m just up-track of the cloud. The threshold vapor pressure deficit that divides the population in two equal groups is 1.57 mb.

Clearly, in a dry environment the cool anomaly, negative buoyancy relative to the Cu core, subsidence, and convergence (downward acceleration) in the cloud margin are stronger than in a moist environment. In our sample to Cu in dry environments are far more buoyant than in moist environments primarily because they contain less liquid water. Closer inspection shows that many penetrations in the moist environment group occurred near cloud top where significant detrainment occurred. In any event, the comparison in Fig. 16 supports the hypothesis that cloud margin subsidence is not “compensating” (a cloud-scale mass continuity response), but rather is
forced by local negative buoyancy due to evaporative cooling in entraining and detraining eddies. This finding is generally consistent with findings in Rodts et al. (2003), who studied shallow Cu over Florida in summer, and with findings in Heus et al. (2008). Gerber et al. (2008), examining mixing properties in RICO cumuli in a composite sense, note that the near-cloud environmental air differs significantly from the distant environmental air. Grabowski (1993) uses theoretical arguments and high-resolution model simulations to demonstrate cumulus-edge buoyancy reversal due to entrainment of dry environmental air. As entraining eddies associated with baroclinically-induced cloud interface instability transfer their energy to smaller scales, turbulence effectively and rapidly mixes dry and cloudy air, resulting in local buoyancy reversal (Grabowski and Clark 1993). Finally, Jonker et al. (2008) use large eddy simulations to confirm that much of the compensating downward mass transport around cumuli occurs in a thin clear-air shell around cumuli.

This conclusion implies that the clear-air subsidence in a field of Cu clouds tends to be more humid than soundings suggest, since clear-air soundings (the ones not contaminated by cloud) are typically collected further from the clouds. Therefore the use of sounding data may underestimate the downward moisture transfer in the environment surrounding Cu, and overestimate of the mean net upward moisture transfer by a field of Cu (e.g., Lin and Johnson 1996; Frank et al. 1996). This may have implications for cumulus parameterizations in NWP and climate models.

6 Conclusions

This paper analyzed the composite horizontal structure of shallow to moderately deep cumulus clouds from the cloud center across the cloud edge into the ambient clear air. The
cumuli were sampled by aircraft in a broad range of environments in three regions: the tropical Atlantic Ocean in winter, the Sonoran Desert under monsoon flow, and the arid high plains of Wyoming in summer. The main conclusions are as follows:

- Cumuli are generally marked by a buoyant core, rising motion, low-level inflow and upper-level divergence. The flow patterns and buoyancy distribution near the cloud top suggest a toroidal ring circulation.
- The cloud margin (roughly within 200 m on both sides of the cloud edge, or, in normalized space, roughly within 10% of the cloud diameter from the cloud edge) is characterized by sinking and downward accelerating flow, relatively cold air, and a rapid decay of liquid water content and droplet concentration towards the cloud edge. Composite evidence suggests that this subsidence is locally forced by evaporative cooling in entraining and detraining eddies, although the cloud margin is characterized more by a minimum in buoyancy flux than of buoyancy itself. The typical lateral entrainment depth of eddies appears to be less than 700 m.

In a follow-up study, these findings will be tested in the dynamically consistent 3D framework of a high-resolution [O(10²) m] cloud-resolving model.

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References


Figure captions

Fig. 1: Effect of flight direction (shown as a bold arrow) on LICOR 6060 water vapor mixing ratio for all cumulus penetrations in RICO-04 (549 cases). The shaded region is cloudy.

Fig. 2: Histograms of the mean properties of the cumuli in three environments. The number of Cu samples in each environment is shown in panel (a).

Fig. 3: Variation of cloud droplet concentration $N_o$ with normalized distance from the cloud center ($x^* = -1$) to the cloud edge ($x^* = 0$). (a) Frequency-by-distance display of the normalized cloud droplet concentration $N_o^*$. The black line indicates the mean. The other plots show the mean variation of $N_o$ with distance for (b) warm and cold clouds (the mean temperature threshold is -5°C), (c) maritime and continental clouds (the mean $N_o$ threshold is 150 cm$^{-3}$), and (d) ascending and descending clouds. In (b-d) and in later figures, the dotted lines indicate the mean plus one standard deviation. The number of cases is listed on top of each plot.

Fig. 4: As Fig. 3, but for the LWC.

Fig. 5: As Fig. 3, but for the mean drop diameter $D$.

Fig. 6: As for Fig. 3, but for vertical air velocity $w$. The normalized distance extends from the cloud center ($x^* = -1$) into the clear air, over a distance matching that in-cloud ($x^* = +1$). Also note the linear scale of frequencies in (a).

Fig. 7: Scatterplot of in-cloud vs. out-of-cloud mean vertical air velocity.

Fig. 8: The cumulative vertical mass flux over an area integrated from the cloud center, for the mean vertical velocity shown in Fig. 6a.

Fig. 9: (top) Variation of the mean horizontal “radial” velocity from the cloud center to the clear-air shell. This velocity is defined to be positive for outbound flow, away from the cloud center. It
is a perturbation value, i.e. the mean between \(-1 < x^* < 1\) is removed for each penetration. Panel (a) contrasts the three environments and panel (b) contrasts flight levels in the upper half of the cloud against those in the lower half. The horizontal divergence resulting from the mean radial velocity is shown in (c) for all cases and in (d) for upper-level vs. lower-level penetrations.

**Fig. 10:** As for Fig. 6, but for air temperature $T$.

**Fig. 11:** As for Fig. 6, but for buoyancy $B$. Also shown in (a) is the vertical buoyancy flux (black & white dashed line).

**Fig. 12:** Mean turbulent kinetic energy for all Cu for the 3 environments.

**Fig. 13:** Histograms of (a) cloud vertical dimensions, and (b) flight level relative to the cloud vertical dimensions. $Z_{\text{pen}}, Z_{\text{base}},$ and $Z_{\text{top}}$ are the penetration level, the cloud base, and the cloud top respectively.

**Fig. 14:** Mean variation of (a) $N_o$, (b) LWC, (c) temperature, (d) vertical velocity, (e) buoyancy, and (f) buoyancy flux with normalized distance $x^*$ for upper-level and lower-level flight levels.

**Fig. 15:** Mean variation of (a) $N_o$, (b) LWC, (c) temperature, (d) vertical velocity, (e) buoyancy, and (f) TKE with physical distance $x$. The dotted line shows the number of penetrations (frequency) as the function of $x$. Note that this dotted line is flat for $|x|<200$ since the minimum cloud width in the sample is 400 m. The cloud edge is at $x=0$ and the cloudy region corresponds with $x<0$.

**Fig. 16:** Mean variation of (a) temperature, (b) buoyancy, (c) vertical velocity, and (d) divergence (assuming radial symmetry) with normalized distance for dry vs. moist environments.
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