Composite Vertical Structure of Vertical Velocity in Nonprecipitating Cumulus Clouds

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ABSTRACT

Vertical transects of Doppler vertical velocity data, obtained from an airborne profiling millimeter-wave cloud radar, are composited for a large number of cumulus clouds (Cu) at various stages of their life cycle, to examine typical circulations patterns. The Cu clouds range in depth between ~500 and 6000 m and are generally nonprecipitating. They were sampled on board the University of Wyoming King Air over a mountain in southern Arizona during the summer monsoon, and over the high plains of southeastern Wyoming. The composite analysis shows clear evidence of an updraft/downdraft dipole in the upper cloud half, consistent with a horizontal vortex ring. A single cloud-scale toroidal circulation emerges notwithstanding the complex finescale structure with multiple vortices, commonly evident in individual transects of Cu clouds. The stratification of all Cu samples as a function of their buoyancy and mean vertical velocity shows that the vortex ring pattern tends to be more pronounced in positively buoyant Cu with rising motion (presumably young clouds) than in negatively buoyant and/or sinking Cu near the end of their life cycle. Yet no reverse vortex ring is observed in the latter Cu, suggesting that the decaying phase is short lived in these dry environments. The vortex-ring circulation pattern is more intense in the shallower Cu, which are also more buoyant and have a liquid water content closer to adiabatic values. Wind shear tends to tilt Cu clouds and their vortex ring, resulting in a broadening of the upshear updraft and downshear downdraft.

1. Introduction

Cumulus clouds (Cu) are important in the general circulation as they dynamically couple the planetary boundary layer to the free troposphere through vertical mass transport and affect the vertical structure of radiative heat flux divergence. The representation of Cu clouds in weather or climate models is challenging (e.g., Randall et al. 2003) since they occur in a broad range of vertical and horizontal scales (e.g., Lopez 1977), and the circulations are generally subgrid scale (e.g., Khairoutdinov et al. 2008). Thus, a number of Cu parameterizations have been developed to represent the effect of subgrid-scale convection on precipitation and the vertical profile of resolved variables. These have focused on deep convection, but more recently they have also addressed shallow convection (e.g., Deng et al. 2003; Bretherton et al. 2004). Such parameterizations make assumptions about the turbulent mixing of Cu clouds with the environment (Siebesma and Cuijpers 1995).

The macroscale geometric properties of Cu clouds are controlled by the way in which a moist buoyant core exchanges air with its cloud-free environment. There are two distinct terminologies for the continuous mixing process between cloudy and clear air: an entrainment event takes place in cloud and a detrainment event evolves outside the cloud edge. Entrainment of ambient air across the cloud edge fundamentally affects the cloud’s dynamics (e.g., Raga et al. 1990; Blyth 1993; Grabowski 1993; Carpenter et al. 1998), and detrainment of cloudy air into the surrounding clear air cumulatively alters the environment (e.g., Perry and Hobbs 1996; Grabowski and Moncrieff 2004; de Rooy and Siebesma 2010; Wang and Geerts 2011).

Entrainment mechanisms have been studied using laboratory simulations, atmospheric observations, and numerical models. Blyth et al. (2005) uses mainly aircraft observations to conclude that Cu clouds behave as shedding thermals, with entrainment occurring near the ascending cloud top and with mixed parcels descending around the edges of the buoyant updraft core. This suggests that the source level of much of the diluted air measured at some level generally is at a higher level. The large-eddy simulation (LES) study by Heus et al. (2008),
however, shows that the Lagrangian tracking of air parcels reveals little cloud-top entrainment: particle trajectories extracted from the LES runs clearly indicate that the main source of entrainment is lateral. Lateral entrainment yields characteristic horizontal variations of thermodynamic and moisture variables across the cloud edge. These characteristic variations have been documented by means of composite in situ data collected in a large number of aircraft penetrations through Cu and their immediate environment (Rodts et al. 2003; Wang et al. 2009; Wang and Geerts 2010).

Aside from lateral entrainment at any level, much entrainment also appears to result from a cloud-scale vortex-ring (toroidal) circulation entirely contained within the upper portion of the cloud, as suggested by Blyth et al. (2005). Evidence for such circulation includes modeling simulations (Klaassen and Clark 1985; Grabowski and Clark 1993; Zhao and Austin 2005b), observational studies using aircraft data (MacPherson and Isaac 1977; Blyth et al. 1988; Jonas 1990; Blyth et al. 2005), airborne radar data analyses (Damiani et al. 2006), trace gas analyses (Stith 1992), and tank experiments (Woodward 1959; Sanchez et al. 1989; Johari 1992). This toroidal circulation is important because it affects basic Cu characteristics (i.e., entrainment and detrainment, aerosol evolution, drop size distribution, hydrometeor recycling, and precipitation development). The toroidal motion can also dynamically affect the maximum height of Cu turrets, as the associated dynamic pressure deficit in the circulation centers can oppose the suppressing effect of a dynamic pressure high resulting from the interaction between an updraft and the ambient vertical wind shear (Damiani and Vali 2007).

Thus, it is meaningful to examine vortex-ring circulations in a systematic way. Cloud radar observations by Damiani et al. (2006) and Damiani and Vali (2007) improved our understanding of cloud-top circulations, but they only showed the results from select case studies. Vertical velocity statistics of Cu clouds have been examined before (e.g., Kollias and Albrecht 2010; Ghate et al. 2011), but these studies used nonsimultaneous data (from a ground-based profiling radar, not an airborne radar) and they did focus on horizontal variations within clouds. The present study examines the generality of Cu circulation patterns by compositing radar reflectivity and Doppler vertical velocity data from a large number of vertical transects collected in aircraft penetration of Cu clouds. The selection is unbiased as it includes all penetrations, between the Cu entry and exit points, subject only to a minimum cloud width and relative isolation from adjacent clouds. The objective is to show the characteristic vertical velocity and reflectivity structure in Cu, and stratify this as a function of cloud age, cloud size, and ambient shear.

The data sources and analysis method are introduced in section 2. The results are presented in section 3, and their implications are discussed in section 4. The key findings are summarized in section 5.

2. Data sources and analysis method

The Cu samples used in the present study were chosen from clouds penetrated by the University of Wyoming King Air (UWKA) in two recent campaigns: the 2003 High Plains Cu (HiCu) campaign (Damiani et al. 2006) studied high-base cumulus clouds over the high plains of southeastern Wyoming; and the 2006 Cumulus Photogrammetric, In Situ, and Doppler Observations (CuPIDO) campaign (Damiani et al. 2008; Geerts et al. 2008) pursued orographic convection.

The HiCu clouds were relatively cold, with cloud base near 0°C. The HiCu flights were conducted in the afternoon with a well-developed convective boundary layer, and far away from any deep convection. The Cu clouds targeted in CuPIDO formed over the Santa Catalina Mountain range in Arizona close to local solar noon, often before deep convection broke out: some flights were terminated at the first lightning strike over the mountain. Macroscale properties of the sampled Cu and their environment will be discussed in section 3a.

a. Flight-level and sounding data

The UWKA in situ measurements have been discussed in many studies (e.g., Damiani et al. 2006; Wang et al. 2009; Wang and Geerts 2011). Temperature is measured by a reverse flow thermometer, which is an immersion probe developed to minimize in-cloud sensor wetting. The temperature has been corrected for the sensor evaporative cooling bias following Wang and Geerts (2009). The cloud liquid water content (LWC) is estimated using the Gerber particle volume monitor (PVM-100; Gerber et al. 1994) and the cloud droplet concentration \(N_d\) (number of droplets per unit volume) is obtained from the Forward Scattering Spectrometer Probe (FSSP) (Brenguier et al. 1994). Vertical and horizontal air velocities are derived from the UWKA gust probe (Lenschow et al. 1991). We obtained humidity variables from a chilled-mirror dewpoint sensor, whose response time is relatively slow. Therefore, the air is assumed to be saturated relative to water in cloudy regions \((N_d > 10 \text{ cm}^{-3})\). Variables such as buoyancy and equivalent potential temperature are then computed from the corrected temperature and humidity estimates. The buoyancy \(B\) (m s\(^{-2}\)) is computed as
Here \( T_v \) is the mean environmental virtual temperature, \( T'_v \) is the virtual temperature perturbation, \( p \) is the mean environmental pressure, \( p' \) is the pressure perturbation, and \( r_h \) is the mixing ratio of liquid and/or frozen water.

The in-cloud value of specific humidity is assumed to be the saturated value computed from local temperature and pressure, while the measurement from the chilled-mirror dewpoint sensor is used for the specific humidity outside of cloud. The expression for \( B \) involves perturbations: the reference state is computed over a distance of 400 m on both sides of the cloud.

Proximity GPS Advanced Upper-Air Sounding (GAUS) data were collected as part of the CuPIDO experiment (Damiani et al. 2008). The environment in which Cu clouds formed over the Santa Catalina range was profiled at 30–60-min intervals. The GPS soundings were released from the upwind side, within 20 km of the highest point in the Santa Catalina range. No radiosondes were released as part of the HiCu experiment. The closest operational radiosonde was launched in the late afternoon (0000 UTC) from Denver, 200–300 km away. Therefore, the UWKA in situ data were used during take-off and landing at Laramie’s airport to construct the most representative profile of temperature, humidity, and wind.

b. Cloud radar data

The UWKA carries a 94-GHz (W band), multiple-beam Doppler radar, the Wyoming Cloud Radar (WCR; Pazmany et al. 1994; Wang et al. 2012). The WCR equivalent reflectivity (reflectivity for short) and Doppler velocity are used in this study. The WCR operates mainly in two modes: up/down profiling mode and vertical-plane dual-Doppler (VPDD) mode (Fig. 1 in Damiani et al. 2006). The WCR profiling data are used for the composite analysis: these data portray the vertical structure of an echo over its entire depth except for a \(-250\)-m-deep “blind” zone centered at flight level. In VPDD mode the along-track 2D hydrometeor motion below the aircraft can be derived: the vertical component is almost entirely determined by the nadir beam, and the along-track component by a combination of the nadir and slant forward beams. The extraction of the echo’s ground-relative motion from the Doppler velocity measured from a moving platform, and the dual-Doppler synthesis, are discussed in Leon et al. (2006) and Damiani and Haimov (2006). In a turbulent environment such as a Cu cloud, the velocity uncertainty is about 1 m s\(^{-1}\) at ranges less than 2 km (Damiani and Haimov 2006). The error sources of the WCR single and dual-Doppler velocity are quantified in Damiani (2005).

c. Sample Cu transects

An example of the combined in situ and vertical profile WCR data is shown in Fig. 1. Figure 1f visually illustrates the target Cu just before penetration. The flight-level droplet count (Fig. 1b) indicates the width of the visible cloud along the track, in this case \(\sim 3\) km.

This Cu features not one but two updraft cores extending from low levels to cloud top. These buoyant cores are surrounded near the cloud top and edges by downdrafts. The WCR reveals another Cu cloud to the right, \(5 < x < 6.5\) km, entirely below flight level. This cloud must be decaying because the WCR vertical velocity is negative throughout, the echo is strong and at a low elevation (because of downward transport), and no cloud droplets are encountered at flight level. The pockets of high reflectivity in this cloud (\(>5\) dBZ) are probably due to ice that formed higher up at an earlier stage. Forward-looking cockpit camera imagery reveals no cloud in this region, but some haziness due to virga. The mean flight-level temperature is \(-7.2^\circ\text{C}\). The 2D-C probe does not sample any ice particles between 5 and 6.5 km, which may due to the probe’s small sample volume, or simply because this old Cu has descended below flight level. The buoyancy is positive above this cloud, likely because stratified ambient air is drawn down above the collapsing Cu.

The horizontal flow is generally weaker than the vertical flow in this Cu, according to flight-level data and dual-Doppler synthesized data (Fig. 1e). The latter reveals that the updraft-downdraft dipole between 4.0 and 5.0 km, seen in Fig. 1d, is part of a closed circulation, with flow toward the cloud center at low levels and divergent flow near the cloud top. The low-level inflow is sharply convergent near along-track distance \(x = 4.3\) km (Fig. 1e), consistent with a strong updraft aloft (Figs. 1a,d). Possibly this target cloud is in the process of splitting in two.

An example of the dual-Doppler synthesized winds in the upper portion of a HiCu cloud is shown in Fig. 2. Some select streamlines are added to highlight a vorticity dipole, consistent with a somewhat tilted vortex ring in three dimensions. The horizontal wind field (Fig. 2b) clearly reveals divergent flow near the cloud top. A strong updraft core is evident between the two vortices (Fig. 2c). This updraft is flanked by downdrafts; the stronger one is on the downshear side. The lack of measurable echoes in the lower part of this updraft suggests small cloud droplets and no ice in this region. The circulation clearly carries the hydrometeors around the updraft core. There is no clear evidence of convergent
flow at the bottom part of this transect, in part because of inadequate echo strength. The bottom part of this transect roughly corresponds with the midlevel between cloud base and top, according to an independent estimate of cloud-base height.

Individual Cu clouds can be a conglomerate of multiple turrets, each with a vortex-ring circulation and with a life cycle shorter than that of the entire cloud. A single updraft and single vortex-ring structure are evident in the upper part of one small CuPIDO Cu (Fig. 3d), as well as in the HiCu Cu shown in Fig. 2. Other examples, such as the one in Fig. 1 and the Cu in Figs. 3a,b, reveal two separate updrafts near the cloud top. Different ages are likely: a third core rising from the bottom-right side of the cloud in Fig. 3b probably is young, while the collapsing tower in the bottom-right side of Fig. 1d probably is old. Some Cu towers are erect with a symmetric vortex ring (Fig. 3d), while others feature a tilted updraft and vortex-ring structure. For instance, both the WCR-retrieved reflectivity and vertical velocity fields in Figs. 3e,f are tilted to the right because of the horizontal wind shear from left to right. This Cu is characterized by a rather low reflectivity, possibly because of enhanced entrainment and erosion by shear.

d. Reflectivity attenuation

The WCR often lacks the sensitivity to detect entire Cu clouds. The cloud base is usually not detected for two reasons. One is that droplets near the cloud base are generally too small, at least in updraft regions. The other is that the clouds composited in this study mostly were penetrated near the top, in fact some 80% of the flight levels are in the upper half of the target cloud, as will be shown later.

Radar power is attenuated by water along the path. The WCR nadir beam can detect echoes down to about −32 dBZ at a range of 0.5 km and −28 dBZ at...
Here we define the minimum detectable reflectivity as the received power at two standard deviations above the mean system noise, which increases with the square of the radar range. The cloud transect examples in Figs. 1 and 3 clearly show a decrease in reflectivity with range. The attenuation by liquid water is highly dependent on drop size: the power extinction coefficient at the WCR frequency (94 GHz) is as large as 20 dB km$^{-1}$ (g m$^{-3}$)$^{-1}$ of cloud water for drops of 1-mm diameter (Lhermitte 1990). But the 2D-C probe did not record any droplets with diameters of 100 μm or larger in any of the clouds illustrated in Fig. 1 and 3 (with one exception at 650 μm diameter, possibly an artifact). For droplets smaller than 100-μm diameter the power extinction coefficient at 94 GHz is only 5.0 dB km$^{-1}$ (g m$^{-3}$)$^{-1}$ of cloud water, which includes absorption by water vapor, about 0.2 dB km$^{-1}$ in the present conditions (Vali and Haimov 1999). The two-way path-integrated attenuation for most Cu clouds included in this study is 10 dB km$^{-1}$ (g m$^{-3}$)$^{-1}$ of liquid water.

The observed decrease in reflectivity with range below flight level is 16.0 dB km$^{-1}$ for the cloud in Fig. 1c (x < 5.2 km, i.e., excluding the echo in the bottom-right corner of the transect) (9.7 dB km$^{-1}$ for the cloud in Figs. 3a and 4), while the measured mean flight-level LWC in this cloud is 1.43 g m$^{-3}$ (1.04 g m$^{-3}$ for the cloud in Fig. 3a). Adiabatic LWC increases with height, thus a high estimate for two-way path-integrated attenuation, assuming a constant LWC from flight level down, is 14.3 dB km$^{-1}$ (10.4 dB km$^{-1}$ for the cloud in Fig. 3a). The reflectivity lapse rate expected from attenuation is only slightly less than the observed lapse rate, suggesting that the observed increase in reflectivity with height toward flight level is largely due to attenuation, and less to cloud droplet growth. Above flight level, the reflectivity lapse rate expected from attenuation because of flight-level LWC may be an underestimate if the LWC increases further with height. In any event, the reflectivity lapse rate expected from attenuation is close to the observed lapse rate above flight level as well (Figs. 4a,c). Given the unknown variability in LWC in a Cu cloud, it is impossible to “correct” the reflectivity for attenuation, and thus it is impossible to derive the true reflectivity profiles in the sampled Cu clouds. In some cases high reflectivity values are observed in pockets, sometimes at a significant range from the aircraft, especially in the HiCu cases. Such pockets are probably due to ice particles. An example that appears to be a pocket of ice crystals can be seen in Fig. 1c, in the bottom-right region.

It should be noted that the quality of the WCR Doppler velocity, which is the focus of this paper, is not affected by attenuation, as long as the signal remains above the range-dependent threshold reflectivity. Also, the cases shown in Figs. 1 and 3 have a relatively high LWC. The average LWC in all Cu clouds composited in the present study is only 0.72 g m$^{-3}$. Nevertheless, the bottom half of the most clouds in the composite is not or only marginally detected by the WCR and thus lacks Doppler velocity data. For instance, a sounding released within 30 min and 30 km from the Cu cloud in Fig. 1 indicates that the ambient lifting condensation level (LCL; i.e., the cloud base) in the convective boundary layer is 3960 m MSL; that is, 1.4–1.8 km below the lowest level with WCR data in the target cloud. Thus, the emphasis will be on the upper part of the cloud, which is generally well captured by the WCR.

e. Radar vertical velocity

The vertical velocity shown in Figs. 1–3 is the hydrometeor vertical motion, which is the sum of the vertical
air motion and the (downward) fall speed of the cloud particles. The WCR reflectivity and flight-level particle probe data indicate that the hydrometeor diameter typically is small, from which it can be inferred that the fall speed (or “terminal velocity”) is small. Frisch et al. (1995) found that droplet fall speed in warm clouds can be ignored at millimeter-wave reflectivity values of at most $217 \text{ dBZ}$. The reflectivity of the target clouds is rather low, with a typical value of $220 \text{ dBZ}$ at a range of 0.5 km. The fall speed of droplets with a diameter of $100 \mu m$ is $0.3 \text{ m s}^{-1}$ and increases rapidly for larger drops (Pruppacher and Klett 1997, see their Figs. 10–23). Most clouds in the composite had very few particles larger than $100 \mu m$ at flight level, according to the 2D-C data. Some particles larger than $100 \mu m$ are nonspherical (i.e., ice, whose fall speed is no larger than that of water of the same diameter).

This suggests that the typical fall speed is negligibly small compared to the typical convective up- and downdrafts such as those evident in the sample Cu clouds in Figs. 1–3. However, the return power (and Doppler velocity) from distributed targets is dominated by the largest particles in the radar resolution volume. To examine whether the fall speed can be ignored, we compare the flight-level gust probe vertical velocity to the near-flight-level WCR vertical velocity (an interpolation using the nearest three gates along the up and down antennas, about 150–200 m above/below flight level), for all Cu penetrations (Fig. 5). All velocities are averaged over the flight-level width of the cloud. The difference between the two independent measurements plotted in Fig. 5 is subject to much uncertainty, related to (i) how well the horizontal wind contamination due to the off-vertical WCR antenna orientation is removed to obtain WCR vertical velocity, (ii) gust probe vertical velocity errors, and primarily (iii) the spatial mismatch between radar and gust probe measurements in a turbulent environment. For all Cu penetrations, the difference between air and radar vertical velocity is positive on average, indicating falling particles. This difference does not measurably increase with liquid water content or temperature. It does increase with reflectivity. The mean difference is only $0.42 \text{ m s}^{-1}$ for the low-reflectivity ($<20 \text{ dBZ}$) cases in Fig. 5. Also, the correlation between gust probe and radar vertical velocities is very high for the low-reflectivity cases. For these cases, the

![Fig. 3. Transects of (left) WCR reflectivity and (right) vertical velocity for three isolated Cu clouds in CuPIDO: (a),(b) 1805 UTC 9 Aug 2006; (c),(d) 2014 UTC 8 Aug 2006; and (e),(f) 1637 UTC 8 Aug 2006.](image-url)
fall speed can clearly be ignored. The mean difference is 1.16 m s\(^{-1}\) for the high-reflectivity (\(>-20\) dBZ) cases (Fig. 5; i.e., a particle terminal velocity can be detected). But this fall speed is still small compared to convective drafts. The fall speed is about twice as large in HiCu clouds than in CuPIDO clouds. HiCu clouds also tend to have a higher close-range reflectivity and to be deeper and colder. It is impossible to remove the fall speed component because its estimate is highly uncertain, given the attenuation of reflectivity, the frequent presence of ice in higher reflectivity areas, and the uncertainty about riming intensity of ice particles. Thus, the fall speed can and must be ignored in all cases, and to a first order the WCR vertical velocities will be interpreted as air vertical motion.

f. Radar data compositing

To composite cloud structure, the spatial dimensions of each cloud need to be normalized. Height in cloud \(h\) is normalized between cloud base and cloud top (0 < \(h^*\) < 1). The cloud top is defined as the highest echo seen by the WCR above the UWKA during Cu penetration. Near-cloud-top echoes are normally strong enough, but our cloud-top definition is an underestimate when the aircraft track is not right under the cloud top (e.g., for a tilted or cone-shaped Cu). As mentioned before, the cloud base cannot be seen by the WCR, so it is defined as the LCL, computed from potential temperature and mixing ratio data mixed in the lowest 50 hPa above the surface, using proximity sounding data. For CuPIDO cases the closest GAUS sounding (in space and time) was used (section 2a). For HiCu cases we estimate the cloud base as the lowest LCL estimate from aircraft data collected near the ground, just after take-off and/or just before landing.

In total, 248 of all 313 clouds in the composite were penetrated by the UWKA, thus flight-level data of cloud properties such as buoyancy are available. These 248 clouds in the composite contain droplets (as measured by the FSSP), although the FSSP droplet number concentration does not define the cloud edges.

We define the normalized distance \(x^* = 0\) at the cloud center and \(x^* = 1\) at the cloud edge. The WCR-defined cloud edge varies with height. In the present study, the cloud width is defined as the distance between the two outer cloud edges seen by the WCR within 500 m of flight level, and the cloud center is defined as the midpoint between these two edges. Only clouds whose width and depth exceed 400 m are included. Clouds with
a separation of less than 400 m are excluded as well, because those clouds often are part of a single cloud below flight level.

Some adjustment needs to be done to sheared Cu. The above compositing method assumes a rectangular cloud domain with a height-independent cloud center \((x^* = 0)\), but upper-level updrafts tend to be included in the downshear half for sheared clouds. The tilted Cu shown in Figs. 3e,f is one good example: the left cloud edge is near \(x = 0.5\) km, the right edge near \(x = 2.5\) km, thus the height-independent Cu center in normalized space \((x^* = 0)\) is near \(x = 1.5\) km. The upper-level updraft is found near \(x = 2.0\) km (i.e., in the downshear cloud half). The composite data frequency near cloud top is much higher in downshear half clouds than in upshear half clouds.

To remedy this situation, we allow the cloud center to tilt with height: the effective height-dependent cloud center in physical space becomes vertically aligned in normalized space \((x^* = 0)\). An example of this tilt removal process is shown in Fig. 6. The optimal tilt angle is computed from the linear regression line of the cloud center plotted against height.

The two campaigns yield a total of 313 cloud samples (183 from CuPIDO and 130 from HiCu). The composite analysis considers each half cloud as an independent unit. Clearly the two halves in any cloud are not a mirror image, yet conceptually, we are interested in a symmetric pattern, in which both sides are the same (except in case of wind shear, which will be examined separately). The composite Cu structure images could include the symmetric counterpart to match the traditional view of an entire Cu. To save space, the images are not duplicated in mirror view.

The WCR reflectivity and vertical velocity fields for each of the 626 half-clouds are redistributed in a two-dimensional normalized domain \(0 < x^* < 1\) and \(0 < h^* < 1\) with a bin size \(\Delta x^* = 0.02\) and \(\Delta h^* = 0.02\). The bin size \((\Delta x^*, \Delta h^*)\) is selected as a trade-off between limiting the smoothening of the largest clouds and resolution redundancy for the smallest clouds. For instance, for the Cu shown in Fig. 1, the cloud width and depth are about 3.0 km, thus \((\Delta x^*, \Delta h^*)\) corresponds with \((60, 60)\) m. The WCR range resolution is 30 m for the pulse width used in both campaigns (200 ns). At a range of 1 km, the horizontal resolution (radar half power) is 5.5 m (8.2 m) for the nadir (zenith) antenna. This implies, for the cloud in Fig. 1, smoothening mainly in the horizontal \((\Delta x^* \approx 8)\) m, and less in the vertical \((\Delta h^* > 30)\). In rather large/deep cloud, this data redistribution process results in less-defined cloud edges and the smoothening of extreme values. In the smallest acceptable cloud (400 m wide), the normalized bin size corresponds to the WCR horizontal resolution above flight level.

The outer dimensions of the 626 half clouds are the same in the normalized space, and therefore averages (called “composites”) as well as higher moments can be computed, for vertical velocity and reflectivity. For each cloud, bins with a reflectivity less than two standard deviations above the mean noise level are excluded; therefore, the averages in each bin are computed for 626 values at the most. Along the edges and in the lower half of the cloud, composites are obtained from far fewer than 626 values. We require a minimum data frequency of 8% (50 bin values) to compute the composite value, in order to reduce the statistical uncertainty caused by a small sample size. In the data redistribution and compositing processes, radar reflectivity is averaged in units of \(Z\) (\(\text{mm}^6 \text{ m}^{-3}\)). The average \(Z\) then is reconverted to dBZ.

3. Composite structure of nonprecipitating Cu

a. Basic characteristics of the sampled Cu clouds and their environment

The typical environment of the Cu clouds penetrated during CuPIDO is computed from proximity Mobile GAUS (M-GAUS) radiosonde data (Fig. 7). These radiosondes were released in close proximity of the target
Cu clouds, all within 50 km and 1 h of the flight data. The CuPIDO sounding and flight data were collected over the Santa Catalina Range. This is a rather isolated mountain with almost daily Cu development during the monsoon period. The UWKA data were collected during the transition period from shallow to deep convection, typically just before and around local solar noon (Damiani et al. 2008).

The sampled CuPIDO Cu clouds occurred in an environment with low-level potential instability, up to ~4.7 km MSL or ~2.0 km above the Santa Catalina Range. A rapid transition to an environment with weak potential stability occurs at 4.7 km MSL (Fig. 7b). With a cloud base around 3.0 km MSL (Fig. 7c), this environment is suitable for lightning-free Cu development. The mean level of free convection (LFC) is at about 3.5 km MSL (Fig. 7b). The CAPE values for the 23 CuPIDO soundings representing the environment of the 183 clouds included in this study range between 32 and 2547 J kg\(^{-1}\), with an average value of 1024 J kg\(^{-1}\); the soundings’ convective inhibition is very small, up to 50 J kg\(^{-1}\). No close-proximity soundings are available for the HiCu experiment.

The 130 HiCu clouds in this study tend to be more “continental” than the 183 CuPIDO clouds, with a higher cloud droplet concentration (725 vs 248 cm\(^{-3}\) on average). Also, they have a lower LWC (0.54 vs 0.89 g m\(^{-3}\) on average), and a smaller mean drop size (10.3 vs 15.5\(\mu\) m on average; see Fig. 3 in Wang et al. 2009), notwithstanding their greater average depth (3410 m in HiCu vs 2113 m in CuPIDO; Fig. 8b). The HiCu clouds generally have a higher cloud base, sometimes above the freezing level, and are more often glaciated, as suggested by regions of higher reflectivity and, for those clouds that were penetrated, small concentrations of ice particles measured by the 2D-C in some clouds. The sampled Cu in the two environments are generally of the mediocris type. Some 53% of the select Cu clouds are less than

Fig. 6. (a),(b) The WCR reflectivity and vertical velocity of a sheared Cu penetrated at 1637 UTC 8 Aug 2006, plotted using a 1:1 aspect ratio. (c),(d) As in (a),(b), but the cloud tilt has been removed. The dotted lines represent the Cu center (r = 0). The crosses at flight level in (a) indicate the region of cloud water (FSSP droplet concentration >20 cm\(^{-3}\)).
2 km wide, yet some Cu are just over 4 km wide. The cloud aspect ratio (depth to width) varies considerably, with an average value of 1.5.

The broad range of flight-level temperatures (Fig. 8c) reflects the variation in Cu penetration levels. Flight-level temperatures are lower on average for the HiCu clouds. The ambient wind shear vector \( \left( \frac{\partial u}{\partial z}, \frac{\partial v}{\partial z} \right) \), computed from close-proximity soundings in CuPIDO between cloud base and cloud top, is generally quite small, \(< 2 \text{ m s}^{-1} \text{ km}^{-1} \) (Fig. 8d), although substantial shear \( (> 2 \text{ m s}^{-1} \text{ km}^{-1}) \) is present in about a third of the clouds. The range of flight-level average vertical velocities in the 313 cloud samples is wide (Fig. 8e), implying that all stages in the life cycle of Cu towers are included. While the majority of clouds are marked by rising air motion at flight level, a significant fraction of the sampled Cu is in a decaying phase with mainly sinking motion. The “mean WCR vertical velocity” (Fig. 8f) is a 2D average above and below flight level where the return power is at least two standard deviations above the range-dependent noise level. The mean WCR vertical velocity averages at near zero \((0.20 \text{ m s}^{-1})\), that is, cloud-scale downdrafts are nearly as common as downdrafts (ignoring fall speed), although the mean gust probe vertical velocity for all penetrated Cu clouds is higher \((1.25 \text{ m s}^{-1})\). Its distribution is positively skewed (Fig. 8e). Peak WCR updrafts are as strong as \(15 \text{ m s}^{-1}\), but 90% of the clouds have peak updrafts less than \(10 \text{ m s}^{-1}\) (not shown). A significant minority (39%) of the Cu clouds are negatively buoyant on average (Fig. 8h).

In summary, the dataset of 313 Cu penetrations in this study represents mostly relatively shallow, non-precipitating, weakly sheared Cu in a range of dimensions and Cu life cycle stages. Negatively buoyant, sinking Cu may be overrepresented compared to the true distribution. The likely explanation is the time lag between targeting and penetrating a candidate cloud. But the composite results will be stratified by means of cloud buoyancy and vertical velocity.

b. Composite vertical velocity and reflectivity patterns

The composite WCR vertical velocity for 626 half clouds from CuPIDO and HiCu, derived as discussed in section 2f, is shown in Fig. 9a. The lower half of the clouds remains undetected in most clouds (Fig. 9c), and the cloud base is never detected, in part because of the weak echo expected from small droplets near the cloud base; the other reason is attenuation, since the UWKA mostly flew in the upper half of the clouds (black curve in Fig. 9a).

The radar reflectivity composite (Fig. 9b) is strongly affected by the flight level distribution, because of attenuation (section 2d). But the composite reveals three interesting horizontal variations from cloud center to edge. First, in the upper cloud half the reflectivity is quite uniform, with only a slight maximum near \(x^* = 0.5\). Since the measurement of reflectivity is a combination of droplet concentration and droplet size distribution, this implies that any coherent, cloud-scale circulation does not lead to substantial hydrometeor size sorting in a broad region across the upper cloud half. [This does not exclude significant size sorting over a shallow depth in individual clouds, as documented in some case studies (e.g., Knight et al. 2008).] Second, a significant reflectivity decrease occurs only near the very edge (\(x^* = 1.0\)), suggesting that lateral entrainment of dry air is confined to a small region close to Cu edge. This is consistent with

Fig. 7. (a) Average profiles of temperature \(T\) and dewpoint temperature \(T_d\) obtained from 23 M-GAUS sondes released at Windy Point on the south flank of the Santa Catalina Range in Arizona during UWKA flights between 24 Jul and 17 Aug 2006. (b) As in (a), but for potential temperature \(\theta\), equivalent potential temperature \(\theta_e\), and saturated equivalent potential temperature \(\theta_e^*\). (c) As in (a), but for specific humidity \(q_v\) and saturated \(q_v\). The horizontal solid lines in (b),(c) are the mean LFC and LCL, respectively, and the horizontal dashed lines are the mean ±1 standard deviation.
FIG. 8. Histograms of the mean properties of the 183 Cu in CuPIDO (solid line) and the 130 Cu in HiCu (dotted line) included in the composite: (a) cloud width, (b) cloud depth, (c) flight-level temperature, (d) ambient wind shear, (e) gust probe vertical air velocity, (f) WCR mean vertical velocity, (g) flight-level LWC, and (h) flight-level buoyancy. Shear is not estimated for the HiCu cases because no close-proximity soundings were available. In situ values such as LWC are available only for the subset of 248 clouds penetrated by the aircraft; the aircraft flew above the remainder of the clouds.
the finding of Wang et al. (2009), who used flight-level measurements. And third, the lower cloud half reveals a remarkable echo deficit near the cloud center. Such a deficit can be seen in the cloud in Fig. 2. A low-level echo deficit surrounded by a “curtain” of higher reflectivity is found especially in the subset of clouds that are more buoyant, the narrower ones, and those with a more vigorous core updraft (not shown). It is reminiscent of the bounded weak-echo region in supercell storms.

Two observations stand out in the composite of radar vertical velocity (Fig. 9a). First, sinking motion dominates the lower part of Cu, up to about $h^* = 0.6$. Second, a clear dipole is present in the upper cloud half, with rising motion near the center and subsidence in the periphery ($x^* > 0.5$). This suggests a cloud-top vortex-ring circulation, with an average vertical velocity gradient of about 4 m s$^{-1}$ across the cloud radius. By 2D continuity, the increase in vertical velocity with height at midlevels in the Cu core is consistent with horizontal convergence. There is some evidence of cloud-top vertical deceleration and thus divergence; this evidence is stronger for the more buoyant clouds and those with stronger core updrafts (see below). The horizontal reflectivity variation in the upper cloud half is consistent with such circulation (Fig. 9b): note the slight deficit at the center and higher reflectivity values between Cu core and Cu edge ($0.3 < x^* < 0.7$; i.e., in the transition zone from rising motion to sinking motion. Droplets grow in the updraft in the Cu center and are carried outward by the divergent cloud-top flow. Farther along the vortex-ring flow, entrainment and subsidence lead to reflectivity decrease.

Further evidence for a vortex-ring circulation comes from the distribution of the flight-level along-track wind, as measured by a gust probe, for 248 Cu clouds (Fig. 10). In Fig. 10b the cloud-mean along-track wind component is removed prior to compositing, to highlight the cloud-relative flow. Composite data are only shown where the data frequency exceeds 20, to reduce statistical uncertainty. Spatial dimensions in Fig. 10 are normalized as before, with the same bin dimensions. In the upper part of the data domain, near the cloud top, the along-track wind is to the left (negative) on the left side of the Cu center, and to the right on the right side. This implies divergence, with a magnitude of $\sim 4$ m s$^{-1}$ across the cloud diameter. This is consistent with the flow in the upper part of two counter-rotating vortices. Flight-level winds capture the upper-level divergence better than the WCR vertical velocity (Fig. 9a), but they are inferior at capturing convergence at lower levels, because of the lack of aircraft penetrations below $h^* = 0.5$ (Fig. 10c).

c. The cloud-top vortex ring in developing and decaying Cu clouds

From a simple stability argument, one expects convection to be more intense (and thus the radar reflectivity higher) under higher buoyancy and/or higher updraft speed. This is not the case for the composite of Cu clouds examined herein (Fig. 11), in fact, the (weak) negative correlation counters this expectation. The reason relates to Cu life cycle. A positive correlation is likely to apply to nonsimultaneous peak values for each cloud during its life span. The scatterplot in Fig. 11 applies to
To study the effect of Cu life cycle stages on the circulation pattern, we stratify all the Cu in two subgroups, based on 2D-averaged WCR vertical velocity (Figs. 12a,b), as well as buoyancy (Figs. 12c,d). The reason is that developing young Cu clouds tend to be positively buoyant with rising motion while decaying Cu towers are negatively buoyant and become subsident. The composite results indicate that rising Cu tend to have a deeper updraft/downdraft dipole, with stronger toroidal vorticity (cf. Figs. 12a and 9a), suggesting that the vortex-ring circulation is more pronounced in relatively young Cu. The vorticity maximum (-∂w/∂x*) in the subset of rising Cu is displaced toward the cloud margin, where the subsident flow is almost as strong as in the total population. A stronger and wider vortex-ring circulation early in the Cu life span may imply that the entrainment of dry ambient air is more vigorous in developing Cu than decaying Cu, since the ambient air is drawn into the rising thermal at the bottom of the vortex ring (Blyth et al. 1988; Carpenter et al. 1998; Damiani et al. 2006).

The toroidal vorticity is larger and slightly deeper also for the more buoyant subgroup (cf. Figs. 12c and 9a), suggesting that the toroidal circulation is buoyancy driven. It is remarkable that in older clouds [i.e., those with near-zero or negative buoyancy (Fig. 12d) and those with prevailing subsidence (Fig. 12b)], the toroidal vorticity in the upper cloud half still has the same sign (into the page), although it is much weakened. Even the most negatively buoyant clouds in this study do not reveal a reversed vortex-ring circulation in the upper cloud region. Such reversed circulation does exist in downbursts (e.g., Fujita 1978).

In summary, the vortex-ring circulation is an intrinsic part of developing, buoyant, rising Cu. This circulation tends to become confined to the Cu top as the Cu matures, and it decays as the cloud’s buoyancy and ascent decay.

d. The effect of cloud size on the cloud-top vortex ring

Previous work has shown that the vortex-ring circulation is often confined to the cloud top (e.g., Blyth et al. 2005; Damiani et al. 2006). The WCR composite of 313 Cu clouds appears to confirm this (Fig. 9a), but the vortex is smeared out in the averaging over a range of cloud depths. To better define the primary Cu circulation structure, we stratify the WCR transects by cloud depth (Figs. 13a,b). In shallow Cu the toroidal vortex extends over much of the cloud depth, while in deep Cu it is confined to the upper third of the cloud, with strong upward acceleration (∂w/∂z*) and (implied) horizontal convergence (-∂w/∂x*) below the center of this vortex. Yet shallow Cu have a higher toroidal vorticity (-∂w/∂x*).
Does the toroidal vortex scale with the cloud width? If it does, then there should be little composite vertical velocity difference between the narrow and wide subsets in normalized space. The difference is relatively small indeed (Figs. 13c,d): the toroidal updraft is only slightly wider and deeper in narrow clouds.

The higher toroidal vorticity in shallow Cu is consistent with the higher flight-level buoyancy in these clouds.

FIG. 11. Scatterplots of 2D-averaged WCR reflectivity as function of (a) mean flight-level buoyancy and (b) 2D averaged WCR vertical velocity, for all clouds in this study [only the penetrated clouds in (a)]. WCR reflectivity and vertical velocity are averaged over the upper half of the 2D domain only, from the cloud midpoint ($h^* = 0.5$) to the cloud top ($h^* = 1$).

FIG. 12. Variation of WCR Doppler vertical velocity in normalized space as in Fig. 9 for different subsets: (a) rising Cu and (b) sinking Cu. The discriminating variable is the WCR mean vertical velocity shown in Fig. 7f. The threshold value is the one that partitions the total population in two equal parts (the modus), in this case 0.16 m s$^{-2}$. (c) More buoyant Cu and (d) less buoyant Cu for the 248 clouds penetrated by the UWKA. The modus cloud-mean buoyancy is +0.006 m s$^{-2}$.
Remarkably, the upper part of all Cu is negatively buoyant (overshooting top), especially the deeper Cu. The buoyancy estimation [using Eq. (1)] involves careful analysis of temperature following Wang and Geerts (2009). Still, it may be somewhat underestimated, especially near the cloud exit region (Wang and Geerts 2009). In any event, our best buoyancy estimation suggests that the vortex’s ascent branch is buoyant in shallow Cu but negatively buoyant in deep Cu.

We also examine flight-level LWC, normalized by the adiabatic value $LWC_a$ (i.e., $LWC^* = LWC/LWC_a$). $LWC_a$ is computed for each Cu penetration from the LCL pressure and temperature and the flight level following Albrecht et al. (1990). If the adiabatic fraction $LWC^*$ equals 1.0, then the air parcel is undiluted. Three observations stand out (Figs. 14c,d). First, the maximum $LWC^*$ is about 0.35, suggesting that quasi-undiluted cores are rather rare in these small Cu, and that in most sampled clouds the boundary layer air has been thoroughly modified by entrainment. Second, $LWC^*$ decreases from cloud center ($x^* = 0$) toward cloud edge ($x^* = 1$) for both shallow and deep Cu, suggesting penetrating lateral entrainment, consistent with previous work (e.g., Heus and Jonker 2008; Wang et al. 2009). Third, deep cumuli have significantly less $LWC^*$ than shallow Cu. This likely reflects a decreasing frequency of adiabatic cores with increasing cloud depth over which lateral entrainment can act. The preponderance of relatively narrow clouds (Fig. 8a) and low ambient humidity probably explain why few near-adiabatic cores were sampled.

e. The effect of ambient wind shear on the cloud-top vortex ring

Wind shear imposes a dynamic pressure perturbation gradient on a rising Cu tower, which tilts the cloud downshear and allows ambient air to circumvent the cloud obstacle [e.g., Fig. 2.8 in Markowski and Richardson (2010)]. Modeling work shows that the main updraft in a sheared Cu occurs on the upshear side, while a wide downdraft develops on the downshear side (e.g., Cotton and Tripoli 1978); and that the ambient cloud-relative flow and the increased cloud surface area increase cloud-edge entrainment and thus reduce the maximum height the Cu tower will reach (e.g., Hinkelman et al. 2005). Damiani et al. (2006) interpret
the impact of ambient wind shear in terms of a tilt in the toroidal circulation: shear causes the normal to the ring vortex to tilt from a vertical to a downshear direction, resulting in an upshear updraft and a downshear downdraft near cloud top. We now examine the effect of shear on Cu vertical structure, with a focus on the typical vertical velocity structure in a subset of Cu clouds that experience significant shear.

That Cu clouds tend to tilt in a downshear direction is obvious. For the cloud shown in Figs. 3e,f, the estimated along-track shear vector is a modest 0.6 m s\(^{-1}\) km\(^{-1}\) from left to right. Near the cloud top the updraft (downdraft) clearly is on the upshear (downshear) side. The reflectivity is quite low notwithstanding the cloud depth. The average and maximum WCR reflectivity of all 183 CuPIDO clouds decreases with the magnitude of the wind shear, suggesting that shear inhibits droplet growth (Fig. 15). Wind shear is computed for the CuPIDO clouds from the nearest-in-time M-GAUS sounding, over the depth of the Cu (cloud base to top). In Fig. 15, reflectivity is divided by cloud depth, since to a first order reflectivity increases with cloud depth, and the
The purpose of Fig. 15 is to isolate the effect of wind shear. The wind shear in Fig. 15 refers to the total shear vector (as in Fig. 8d), not just the along-track component.

For the WCR composite analysis, 75 of the 183 CuPIDO samples are excluded because the wind shear component along the flight track either changes sign between the cloud base and top, or is very weak. All HiCu clouds are excluded as well, because the soundings are too far removed to estimate wind shear near the target clouds. That leaves a total of 108 Cu clouds.

The composite vertical velocity structure of these 108 clouds is shown in Fig. 16. Note that clouds tilted downshear are rendered upright for these Cu by allowing the cloud center axis ($x^* = 0$) to tilt with height (section 2f). It can be observed that the upshear side has a broad updraft, flanked by a narrow downdraft along the cloud edge. On the downshear side subsidence occupies a broader region, especially at low and midlevels in the cloud. This composite is broadly consistent with modeling studies.

4. Discussion

This study analyzes vertical velocity transects for 313 Cu, in order to study the typical flow field in Cu clouds. The Doppler vertical velocity field of individual Cu clouds (e.g., Figs. 1 and 2) shows that flow field is complex, with multiple vortices of different sizes and strengths. Multiple buoyant cores and vertical drafts at different life stages may be present in a single cloud, but usually cumulus tops are characterized by a single updraft core and a single vortex ring. While this is well known (e.g., Blyth et al. 2005; Damiani et al. 2006), we are not aware of any analysis of the composite cumulus flow structure based on so many cloud penetrations.
Two compositing approaches are possible to characterize the typical flow field in Cu clouds. One approach, used in this study, is cloud based: the clouds’ horizontal and vertical dimensions are defined from radar and ancillary data, these dimensions are normalized, and average reflectivity and vertical velocity patterns are examined. If the sample was larger, meaningful probability distributions around these averages could be examined.

The second approach is flow based: circulation features are identified, spatially normalized, and composited. This approach is the topic of a follow-up study (Y. Wang and B. Geerts 2013, unpublished manuscript). It requires dual-Doppler wind fields, and is inherently more subjective than a cloud-edge-based compositing, especially because the boundary between coherent (thermally driven) and turbulent circulations is ill-defined. One drawback of our dataset is that dual-Doppler ($u, w$) synthesis is only possible below the flight level, and thus, to capture the full vortex-ring circulation, flight tracks above the cloud top must be used, yielding no cloud in situ information.

The averaging process over numerous clouds in the cloud-based approach filters out the finescale vortex structure, and the result is a single-ring vortex pattern (Figs. 9a and 10a). The vortex-ring diameter roughly scales with the radius of the cloud (Figs. 13c,d): the vorticity maximum occurs near $x^* = 0.5$. The vortex ring appears to be confined to the upper half of the cloud, centered near $h^* = 0.75$. Horizontal divergence just below cloud top (Fig. 10) and convergence below the core updraft (inferred from air mass continuity) add evidence to this interpretation.

The ubiquity of a cloud-scale vortex-ring structure suggests that this circulation is an inherent component of the dynamics of Cu clouds and a lead entrainment mechanism, especially in the Cu development stage, as suggested by Blyth (1993). A cloud-scale vortex-ring circulation may reduce the core buoyancy more effectively than laterally mixing small-scale eddies, because the typical lateral mixing length is only 10%–15% of the cloud diameter (Wang et al. 2009; Wang and Geerts 2010). The height of coherent, entraining flow is not clear from the present study. While the vortex ring appears to be confined to the upper half of the cloud, the subsidence in the cloud margin decelerates most rapidly in the lower half (near $h^* = 0.3$; Fig. 9a). To document the depth and intensity of coherent lateral inflow, a flow-based compositing approach is needed, using dual-Doppler wind data, or flight-level kinematic data uniformly distributed at all cloud levels.

Cumulus clouds are traditionally divided into three life cycle stages: young Cu with strong vertical growth and upward mass flux, mature Cu in which the entrainment of ambient air is in balance with detrainment from cloud to environment, and decaying Cu in which downward mass flux dominates and Cu mix into the environment (Stull 1985; Zhao and Austin 2005a; Heus et al. 2009). The vortex-ring circulation is found to be more common and more intense in young, positively buoyant, rising Cu than in decaying Cu (Fig. 12). No reverse vortex ring is observed in the Cu in their decaying stage, suggesting that this phase is too short lived for the flow field to adjust to the buoyancy reversal (Fig. 12).

5. Conclusions

This observational study is the first one to examine typical circulation patterns of cumulus clouds by compositing the Doppler vertical velocity data from an airborne profiling radar. The cloud-based composite consists of 313 nonprecipitating Cu clouds captured in various stages of their life cycle. The main conclusions are as follows:

1) A horizontal vortex ring entirely or largely contained within the upper half of the cloud is generally present. This single-ring vortex emerges notwithstanding the complex multivortex structure commonly evident in individual transects of Cu clouds.

2) Evidence for a vortex circulation comes from a clear updraft-downdraft dipole, and from cloud-top horizontal divergence. The Doppler radar transects reveal convergent flow below the vortex-ring center. The cloud-top circulation does not cause any significant hydrometeor sorting: the radar reflectivity is rather homogenous in the upper cloud half.

3) The vortex-ring circulation pattern tends to be more pronounced in positively buoyant Cu with rising motion than in negatively buoyant and/or sinking Cu near the end of their life cycle. In this cloud-scale composite, this vortex circulation is also more intense in relatively shallow and narrow Cu, possibly because they are younger.

4) Cumuli and their cloud-top vortex are tilted by shear, such that the upshear side of Cu is dominated by rising motion, whereas a broad region of subsidence motion characterizes the downshear side. The radar reflectivity of Cu of a given depth tends to decrease with the magnitude of shear, implying that wind shear tends to inhibit droplet growth.

These composite observational findings can serve as useful validation material for LES representations of nonprecipitating Cu clouds.

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