Cloud Microphysical Structure Analysis Based on High-Resolution In Situ Measurements^①

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ABSTRACT: This study investigates the microphysical parameters and shapes of droplet size distributions (DSDs) along three aircraft traverses of developing convective clouds during Cloud Aerosol Interactions and Precipitation Enhancement Experiment (CAIPEEX) Phase III 2015 at a sampling frequency of 25 Hz. The droplet number concentration (N_c , cm^{-3}), and liquid water content (LWC, g m^{-3}) present steep gradients within zones of a few tens of meters near the cloud edges and relatively gentle gradients in the strong updraft zones. Sometimes, the horizontal LWC distribution resembles a trapezoidal shape with steep LWC and N_c gradients near the cloud edges. The LWC maximums (LWC_{max}) are lower than the adiabatic LWCs, but the high adiabatic fractions in the cloud core indicate low dilution. High $\text{LWC}/\text{LWC}_{\text{max}}$, largest droplets, and narrow and similarly shaped DSDs are found in the regions of high updrafts. Zones of low $\text{LWC}/\text{LWC}_{\text{max}}$ are found close to the cloud edges, where DSDs are highly diverse, containing both large and small droplets. Finally, we analyze the mixing diagrams. Significant in-phase turbulent fluctuations in LWC and N_c were found. The effective radii change slightly across cloud updraft zones but decrease at the zone of low $\text{LWC}/\text{LWC}_{\text{max}}$ ratio close to cloud edges. The spectra of LWC and N_c obey Kolmogorov $-5/3$ turbulence law. The radii of the correlation of LWC and N_c in updraft zones are of several tens of meters. Filaments up to 120–175 m in size are also noticed.

KEYWORDS: Entrainment; Mixing; Updrafts/downdrafts; Convective clouds; Cloud microphysics; Drop size distribution

1. Introduction

The interaction between convective clouds and their surroundings through the mixing and entrainment processes is of great importance in cloud physics because it affects cloud size, lifetime, mass fluxes, and microphysical and radiative cloud properties (Kain and Fritsch 1990; Burnet and Brenguier 2007; Plant and Yano 2015; Khain and Pinsky 2018). According to Norgren et al. (2016), a significant fraction of air in cumulus clouds originates from the cloud surroundings.

The cloud properties are determined by its droplet size distribution (DSD). It is known that the width of cloud DSD increases with height, in contradiction to the diffusion growth theory (Pruppacher and Klett 1997; Khain and Pinsky 2018). Two main mechanisms of broadening the DSD at the diffusion growth stage are usually considered:

- (i) Mixing of clouds and the surrounding air. Studies focused on this branch of investigation include those by Warner (1969, 1973), Baker and Latham (1979, 1982), Lee and Pruppacher (1977), Raymond and Blyth (1986), Hill and Choulaton (1985), Krueger et al. (1997), Su et al. (1998), Jensen and Baker (1989), and Carpenter et al. (1998a,b,c).

- (ii) In-cloud activation of cloud condensation nuclei (CCN) that penetrate the cloud through its base and ascend with cloud droplets formed at cloud base. In-cloud nucleation can occur when supersaturation (SS) within an ascending cloud parcel exceeds the maximum value reached during previous ascent. Ludlam (1980) provided simplified analytical evaluations of convective parcel acceleration that leads to in-cloud nucleation. In-cloud nucleation was numerically simulated by Feingold and Heymsfield (1992) and Pinsky and Khain (2002) who showed that in-cloud nucleation could explain the observed broadening of DSD in undiluted cloud cores. An observational study by Prabha et al. (2011) presented results of unique measurements in deep convective clouds over India. They showed a close relationship between bimodal, multimodal, and wide DSD and the increase in vertical velocity and SS (approximated by an equilibrium value).

Wide DSDs can also be observed in low frequency measurements as a result of spatial averaging of different spectra (Khain and Pinsky 2018). In this sense, high-frequency observations are important in order to measure the true spectrum width.

To reveal the basic effects of mixing on DSDs, many studies have considered simplified models of mixing between two volumes, that is, saturated cloudy and drop-free subsaturated volumes. These volumes form together an adiabatic volume, and the mixing ends when thermodynamic equilibrium is established (Brenguier and Burnet 1996; Devenish et al. 2012; Korolev et al. 2016; Kumar et al. 2017; Pinsky et al. 2016a,b; Pinsky and Khain 2018a). Yet, there are two possibilities for such a mixing state. If the initial relative humidity (RH, %) in the drop-free volume and/or the total droplet number concentration (N_c , cm^{-3}) in the cloudy volume is low, and all droplets evaporate, there are no droplets in the equilibrium state, and the final SS is negative. When there are droplets in

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the mixing volume at the equilibrium state, the DSD depends on the relative mixing and evaporation rates. Two extreme cases are often discussed: extremely fast and extremely slow mixing, known as “extreme homogeneous” and “extreme inhomogeneous,” respectively. In the first scenario, N_c remains unchanged while the droplets partially evaporate and reduce in size at the final equilibrium state (Grabowski 2006; Chosson et al. 2007; Lehmann et al. 2009). In the latter case, the first droplets penetrating the drop-free volume evaporate completely, resulting in the RH in this volume increasing up to saturation, which prevents the evaporation of the remaining droplets. As a result, N_c decreases while the DSD shape and its characteristic parameters, such as mean volume and effective radii, remain unchanged. Pinsky et al. (2016a,b) and Pinsky and Khain (2018b) have considered the time-dependent mixing and evaporation process in such two-volume systems. They found substantial differences between the DSDs of the time evolution results and those expected in the two extreme mixing regimes. In particular, the process of broadening the DSD takes place in both homogeneous and inhomogeneous mixing.

The behavior of DSD in closed volumes, where mixing always leads to a final equilibrium state, substantially differs from the actual mixing process in clouds. This is particularly so at the cloud edges where mixing leads neither to spatial homogenization nor to the final equilibrium state (Pinsky and Khain 2018a). Theoretical studies (e.g., Pinsky et al. 2016a,b) and analysis of in situ measurements (Gerber et al. 2008; Lu et al. 2011, 2014; Lehmann et al. 2009; Bera et al. 2016a) showed that the actual mixing has features from both homogeneous and inhomogeneous mixing. Note that since the RH in clouds is $\sim 100\%$, the mixing types are indistinguishable.

According to de Rooy et al. (2013), the mixing and entrainment taking place at the lateral cloud boundaries has a turbulent nature. As the cloudy volume mixes with the drop-free dry-air volume, turbulent filaments that form near the interface break into smaller vortices. The final homogenization happens by molecular diffusion (Broadwell and Breidenthal 1982; Krueger 1993; Krueger et al. 1997; Su et al. 1998). Entrainment and mixing at the cloud edges lead to a rather complicated dynamical and microphysical structure of this interface.

According to in situ measurements (Gerber et al. 2008; Norgren et al. 2016; Bera et al. 2016a,b; Kumar et al. 2017) and numerical simulations using a Lagrangian–Eulerian model (LEM; Magaritz-Ronen et al. 2016a,b; Khain et al. 2018), the penetration of the dry air penetrating from the surroundings into the cloud leads to a decrease in liquid water content (LWC, g m^{-3}) within several tens to a few hundred meters inside the cloud. This, in turn, decreases the adiabatic liquid water fraction, which is the smallest near the cloud edge, and typically increases with increasing distance from the edge toward the cloud core. Such changes in the cloud microphysical structure were noted in the direct numerical simulations (DNS) performed by Kumar et al. (2017), who compared the results from advanced DNS against high-resolution in situ measurements of microphysical parameters at the edges of convective clouds in India.

Kumar et al. (2017) found that turbulent mixing near the cloud edges is accompanied by the microphysical processes of drop evaporation and release or activation of condensation

nuclei (CN), and thermodynamical processes such as moistening of the environment. This leads to the formation of a humid shell with associated evaporative cooling. This cooling affects the shell downdraft velocities at the cloud edges (e.g., Heus and Jonker 2008).

Despite in situ measurements (e.g., Gerber 2000; Gerber et al. 2008; Gerber 2018; Prabha et al. 2011; Kumar et al. 2017), large-eddy simulation (LES; e.g., Khain et al. 2019), and low parametric cloud models (Pinsky and Khain 2018b, 2019a,b,c), many problems related to entrainment/mixing effect remain unclear. For example, what is the role of the vertical velocity in the formation of DSDs? Or the problem of the largest droplet formation that give rise to drizzle and raindrops in Cu cloud. Some studies assumed that inhomogeneous mixing might lead to the appearance of large “superadiabatic” drops. It is suggested that the decrease in N_c caused by evaporation within a certain volume of air might lead to the formation of droplets larger than what could be expected within the adiabatic ascent from the cloud base (Devenish et al. 2012; Khain and Pinsky 2018). This could happen during the ascent of a cloud volume with low N_c and the development of high SS. Another possibility is that the first raindrops form in the cloud core and then fall along the subsiding shells in convective downdrafts or inside the cloud near the cloud edges (Khain et al. 2013). The broadening of DSD near cloud edges can also intensify the collision process. Another important problem is the formation of bimodal (45% of the cases) and multimodal (9% of the cases) DSDs in nonprecipitating Cu clouds (Schmeissner et al. 2015). The spatial distribution of these bimodal or multimodal DSDs within Cu clouds is not known. Observations are often made at a very coarse spatial resolution of 100 m or worse, making it impossible to track the DSDs formation details to the processes involved.

Yet another problem is determining the sizes (vortices) of the air filament that penetrate the clouds. These lead to internal fluctuations in cloud parameters, depending on their size and quantity (Krueger et al. 1997).

Measurements must be made at high temporal and spatial resolutions to resolve the turbulent eddies and zones of steep gradients when aiming to understand the physical processes related to entrainment and subsequent mixing in clouds. Paluch and Baumgardner (1989) and Gerber (2000) showed that cloud properties measurements at coarse resolutions overestimate real cloud dilution. The necessity of high-frequency microphysical measurements has been recognized for a long time, especially with respect to the problem of the clouds’ interaction with their surroundings. High-frequency measurements in nonprecipitating Cu (Hill and Choularton 1985; Blyth and Latham 1985, 1990) showed significant small-scale fluctuations in LWC and N_c at all distances from the vertical cloud core. Blyth and Latham (1991) reported the results of 10 Hz (~ 10 m) measurements in nonprecipitating Cu clouds in New Mexico. They found that despite high-frequency changes in LWC and N_c , the effective radius (r_e , μm) at any level was essentially independent of both and close to its adiabatic value. Gerber (2000) reported the results of measurement in Cu clouds during the Small Cumulus Microphysics Study (SCMS) held in Florida during 1995. Measurements of LWC and r_e were

made at 1000 and 250 Hz, respectively. Again, high small-scale LWC variability (with spatial scales smaller than ~ 100 m) was found along the aircraft traverses. A low r_e variability along the horizontal passes within clouds was confirmed. The LWC power spectra were found to obey the $-5/3$ law down to scales of a few meters. A substantial decline in the adiabatic fraction (AF) with the increase in distance from the cloud base was found. Observations of droplet spectra in Cu clouds during the SCMS suggested that their LWC was slightly below the adiabatic values (Brenguier and Chaumat 2001). Gerber et al. (2008) evaluated the decrease of AF with height. They also analyzed mixing diagrams plotted for different clouds. Their results showed that LWC has a trapezoidal shape along the cloud traverse, with very steep slope near the cloud edges and much lower gradients inside. The zone width near the cloud edges, where steep LWC gradients occur, was evaluated to be of 20–30 m. The maximum linear size of the entrained parcels was estimated to be a few tens of meters.

High-spatial-resolution measurements in a nonprecipitating Cu clouds [the Cloud, Aerosol, Radiation and Turbulence in the Trade Wind Regime over Barbados (CARRIBA) field experiment] were also performed by Katzwinkel and Siebert (2014) and Schmeissner et al. (2015), using a platform connected to a helicopter with a long steel cable. The measurements of LWC, N_c , and vertical velocity (W) were performed in developing and decaying Cu. It was shown that decaying Cu clouds are more diluted than developing ones. Kumar et al. (2017) presented dependencies between N_c , mean volume radii, and DSD width along two cloud passes during the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) Phase II on 3 November 2011. The measurements were performed at 5 km altitude with a frequency of 10 Hz. Very steep N_c and LWC gradients at the cloud edges were demonstrated. These studies confirmed the results of Gerber et al. (2008) regarding the presence of a narrow interface zone near the cloud edges. Gerber (2018), using 500 Hz in situ data in Cu, collected during the Rain in Cumulus over the Ocean (RICO) experiment, confirmed the homogeneity of r_e . He also reported the existence of zones of reduced r_e values. The RH of entrained air was evaluated to be very high (over 95%). However, even in studies involving high-frequency observations, no detailed analysis of the DSD structure and turbulence was presented, and most were performed in small Cu.

In the present study, we analyzed the microphysics of growing monsoon clouds during the CAIPEEX Phase III in 2014/15. The in situ measurements were performed at a frequency of 25 Hz, which corresponds to a spatial resolution of nearly 3.5 m. Details on CAIPEEX scientific objectives can be found in Kulkarni et al. (2012). We focused on the following main objectives with high-resolution observations: (i) to understand DSD properties in association with the LWC and W , (ii) to determine the relationship between the relative dispersion of DSDs and the rate of LWC decline, (iii) to determine whether the power spectra of LWC and N_c obey the Kolmogorov $-5/3$ law. A specific feature of the study was that it dealt with convective clouds during their developmental stages.

The article is organized into the following sections: section 2 describes the methodology used in analyzing the data and as

the basis for the theoretical calculations, section 3 presents the meteorological conditions, section 4 presents the results, and section 5 presents the discussion and conclusions.

2. Data analysis and methodology

In this study, we used measurements of growing convective clouds over Akkalkot (17.54°N, 76.00°E), located in the rain shadow region of the state of Maharashtra, India. We selected a case study carried out on 10 July 2015, as part of the CAIPEEX. The cloud observations presented here were made in the afternoon hours, from 0750 to 0841 UTC, over the region of interest. Stepwise horizontal penetrations of the tops of growing convective clouds and horizontal passes through their middle section were carried out to study in situ cloud properties, including the mixing and entrainment processes. The cloud passes through their tops were also used to record instantaneous microphysical processes. As a research objective, we measured thermodynamic state parameters, aerosol, CCN, and other trace gas properties during a flight of total of nearly 3.5 h. The cloud base was located at 1.82 km above mean sea level (MSL), and the convective clouds grew to nearly 4.72 km MSL over that location during the time of observation.

Many high-resolution cloud droplet measurements were made by either Fast-Forward Scattering Spectrometer Probe (e.g., Brenguier et al. 1998; Burnet and Brenguier 2002; Wendisch and Brenguier 2013) or Cloud Droplet Probe (CDP) (Lance et al. 2010). A CDP-2, manufactured by Droplet Measurement Technologies (DMT), Longmont, Colorado, was used in CAIPEEX-III to measure cloud properties at a 25-Hz resolution. CDP-2 measures the size distribution of cloud droplets in the range of 2–50 μm . A limitation of the CDP measurement is the appearance of artificial peaks in the smallest droplets range due to uncertainty caused by Mie scattering (Baumgardner et al. 2010). The CDP was equipped with Korolev tips that reduce the hydrometeors shattering effects and minimize the artificial production of smaller hydrometeors (Korolev et al. 2011). Periodic size calibrations of the CDP-2 were carried out during the campaign period.

Vertical velocity data at a 1-Hz resolution obtained from the Aircraft Integrated Meteorological Measurement System (AIMMS) were used to understand in-cloud dynamics. The uncertainty of the vertical wind speed measurement was $\pm 0.75 \text{ m s}^{-1}$ (<https://aventech.com/products/aimms20.html>).

CCN measurements at different SS, that is, at 0.2%, 0.4%, and 0.6%, were made below the cloud base, using a single-column CCN counter (Roberts and Nenes 2005) manufactured by DMT. The power-law fit between CCN and SS yielded the equation $N_{\text{CCN}} = 785 \times \text{SS}^{0.40}$, suggesting that the clouds grew in moderately polluted continental conditions.

For a detailed study of the mixing processes in these convective clouds, we selected three cloud passes at three distances above the cloud base (i.e., cloud depth) 2.92 km (4.72 km MSL), 1.94 km (3.76 km MSL), and 1.72 km (3.54 km MSL). These are referred to as cloud observations (CO) I, II, and III, respectively. The clouds were near each other and drifted toward the southeast direction. The geometrical midpoint of the maximum updraft regime is referred to as a cloud

core. The location along the aircraft traverse was identified with respect to the distance from the cloud core (i.e., DCC, km). These three traverses were selected because each demonstrated unique entrainment and mixing processes characteristics.

The cloud volume was determined by the conditions that $LWC > 0.01 \text{ g m}^{-3}$ and $N_c > 10 \text{ cm}^{-3}$. The microphysical parameters analyzed were spectral width (σ , μm), r_e (μm), and the relative dispersion (ϵ) of the DSDs (ratio of $\sigma/\bar{r}$, where $\bar{r}$ is the mean radius). The value of r_e was calculated from the ratio between the third and second moments of DSD (e.g., Martin et al. 1994). Since mixing with the surrounding air decreases the LWC, we calculated the reduced LWC from the LWC/LWC_{max} ratio, where LWC_{max} is the maximum value along the traverse. The LWC/LWC_{max} ratio was used to analyze the mixing diagram and dispersion relationship. We also found the adiabatic LWC (LWC_{ad}) using a parcel model and calculated the adiabatic fraction, $AF = LWC_{\text{max}}/LWC_{\text{ad}}$. AF is the adiabaticity measure of cloud volume. In undiluted adiabatic volumes, AF is close to 1.

Furthermore, we investigated the power spectra and correlation properties of LWC and N_c . To evaluate characteristic fluctuation scales of LWC and N_c , we calculated their autocorrelation functions within uniform segments of the traverses. These autocorrelation functions were calculated as $B_{q_{\text{norm}}}(x') = \int_0^{L-x'} [q(x+x') - \bar{q}][q(x) - \bar{q}] dx / \int_0^L [q(x) - \bar{q}]^2 dx$ (Smith 2018), where $q(x+x')$ and $q(x)$ are samples of LWC or N_c at the locations $x+x'$ and x along the traverse. $\bar{q}$ is the averaged value of LWC or N_c . The autocorrelation function allows also to evaluate the radius of correlation.

Radius of correlation is often measured at the distance at which the autocorrelation function rapidly falls from its maximum (equal to 1) to zero or to a small value slightly depending on the distance. This small value is usually not turbulent in nature. Within the radius of correlation there exists the correlation between spatial changes of corresponding parameter. Sometimes, the existence of the correlation can indicate the corresponding points are located within the same vortex. Accordingly, the radii of correlation can approximately be considered as typical sizes of vortices responsible for turbulent fluctuations in LWC and N_c .

3. Meteorological conditions

Wind directions and RH over the observational region at pressure levels of 850, 700, and 550 mb on 10 July 2015 are shown in Fig. S1 in the online supplemental material. These data were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis. In the lower troposphere, that is, at 850 mb, a typical monsoonal westerly wind persisted. However, northwesterly winds were found in the midtroposphere (at 700 and 550 mb), indicating the intrusion of a dry continental air mass into the observational region. Note that during the monsoon season, westerly and southwesterly winds are observed up to a height of about 6 km, above which the winds change their direction (Sarker 1966).

Profiles of temperature, potential temperature (θ), and RH, as obtained from the aircraft observation and ECMWF, are shown in Figs. S2a and S2b. The RH profile indicates rapid

drying above 800 mb. For example, the RH drops from 90% at 800 mb to below 60% at 700 mb. The RH in the lower troposphere was high due to the moisture-laden westerly wind from the Arabian Sea, while it decreased rapidly in the mid- and upper troposphere due to the northwesterly wind of dry continental air.

4. Case studies and in situ measurement results

a. General characteristic of clouds in the passes

Three cloud passes (CO-I, CO-II, and CO-III) were considered in the present study. The surrounding RH was about 60% in all cases. The observed LWC values were smaller than their corresponding LWC_{ad} values indicating the presence of diluted cloud volumes, resulting in $LWC_{\text{max}}/LWC_{\text{ad}}$ ratios of 0.72 (3.40/4.75), 0.82 (2.61/3.19), and 0.70 (2.03/2.89) for CO-I, CO-II, and CO-III, respectively. In all cases, the clouds were at the nonprecipitating growing stage.

We separated the traverses into three clusters according to the LWC/LWC_{max} ratio to classify the changes in cloud properties along them. Cluster I ($0.75 < LWC/LWC_{\text{max}} < 1$) corresponds to cloud volumes with slightly reduced LWC (hereafter, small dilution or slightly diluted volumes). Cluster II ($0.3 < LWC/LWC_{\text{max}} < 0.75$) consists of cloud volumes with moderately reduced (moderate dilution) LWC. Cluster III ($0.01 < LWC/LWC_{\text{max}} < 0.30$) consists of cloud volumes with highly reduced (large dilution) LWC. Besides, we used the concept of “cloud region” to describe the dependencies of microphysical and dynamical variables along the traverses on LWC. We distinguished 1) slightly diluted cores with maximum vertical velocities and high LWC and N_c ; 2) cloud edge regions that separate cloud air from the surroundings and are characterized by very high gradients of W , N_c , and LWC; and 3) the regions between the cloud core and the edge regions, referred to as the transition regions, typically have moderate values and spatial gradients of W , N_c , and LWC. Sometimes peaks in vertical speed and LWC are observed in the transition zone. To assign these zones to the transition zone or to the core, we use additional parameters, for example, N_c and the spectrum width.

Figures 1a, 2a, and 3a show number density [$N(D)$, $\text{cm}^{-3} \mu\text{m}^{-1}$] as a function of drop diameter (D , μm), W (m s^{-1}), and σ (μm) along the CO-I to CO-III passes. $N(D)$ is obtained by normalizing the droplet concentrations at different diameters by their width of the CDP diameter bins. These parameters were plotted with respect to the DCC. The dependencies $N(D)$ along the traverses allowed us to analyze DSD changes with respect to DCC.

The cloud pass lengths were nearly 600 m, 1.5 km, and 1 km for CO-I, CO-II, and CO-III, respectively. Convective updrafts in the core region reached 9, 8.9, and 8 m s^{-1} , respectively. The updraft gradually weakened toward the cloud edges, forming transition zones, which were the largest in CO-III. The well-marked upward zone in CO-III was separated by a 100-m wide region of low W at DCC = 0.76 km (near the yellow arrow). The segment of DCC > 1.3 km was possibly associated with the periphery of another cloud.

Figures 1b, 2b, and 3b show the main parameters of DSDs along the traverses: N_c , LWC, and r_e . Even though the lengths

FIG. 1. Variation in microphysical parameters and the vertical velocity along the traverse in CO-I at 4.72 km MSL on 10 Jul 2015. (a) Cloud DSDs, vertical velocity (W , m s^{-1}), DSD width standard deviation (σ) of transects of a convective cloud. The color bar indicates range of droplet number density. (b) LWC (g m^{-3}), total droplet number concentration (N_c , cm^{-3}), and effective radius (r_e , μm). Length of segments [i.e., scale lengths (m)] shown by a color bar of the traverse corresponding to different ranges of the $\text{LWC}/\text{LWC}_{\text{max}}$ ratio are marked as (i) the slightly diluted zone, cluster I ($0.75 < \text{LWC}/\text{LWC}_{\text{max}} < 1$), (ii) transition zone(s), cluster II ($0.3 < \text{LWC}/\text{LWC}_{\text{max}} < 0.75$), and (iii) the cloud edge zone, cluster III ($0.01 < \text{LWC}/\text{LWC}_{\text{max}} < 0.3$) where LWC_{max} is the maximal LWC. DCC is the distance from the point of maximal W . The arrows point at locations for which DSDs are plotted in Fig. 4a. All measurements are at a 25-Hz resolution except W , which was measured at a 1-Hz resolution.

and altitudes of the passes were different, we noted some important common features:

- 1) The DSD widths were minimal in cloud cores with maximum vertical velocities and maximal at the cloud edges; r_e was relatively uniform horizontally at about $10 \mu\text{m}$ in CO-III and $12 \mu\text{m}$ in CO-I and CO-II, despite significant vertical velocity fluctuations. The difference in the values of r_e between updrafts and downdrafts was $1\text{--}2 \mu\text{m}$. A substantial decrease in r_e took place in the narrow zones between updrafts. This uniformity of r_e within clouds was observed by Blyth and Latham (1991), Prabha et al. (2012), and Khain et al. (2013) with 1 Hz; Bera et al. (2016a) with 10 Hz; and Gerber (2018) with 500 Hz measurements. It was also noted in LESs (e.g., Khain et al. 2019).
- 2) There were significant small-scale (turbulent) fluctuations in LWC and N_c along the passes. The fact that r_e was, to a

large extent, uniform indicates that these fluctuations were in phase.

- 3) The maximum values of LWC and N_c were occurred in the cloud core.
- 4) Even though the maximum LWC was observed in the cloud core, LWC and N_c horizontal profile shapes occasionally resembled trapezoids (especially in CO-I and CO-II) with relatively gentle LWC gradients within a segment of high vertical velocities and decreasing values on either side of a constant LWC segment. There were narrow zones of steep gradients near the cloud edges; where AF was lower than in the zones of relatively gentle horizontal gradients.

Similar LWC shapes were observed in high-frequency measurements along the passes in Cu by Gerber et al. (2008) and Katzwinkel and Siebert (2014) as well as in 10-m resolution LESs of a nonprecipitating Cu (Eytan et al. 2019). We saw a

FIG. 2. As in Fig. 1, but for CO-II. Arrows point at locations for which DSDs are plotted in Fig. 4b.

significant similarity in the LWC variations between shallow Cu and developing convective clouds in CO-I, CO-II, and CO-III, particularly near the cloud edges. Several factors could affect the LWC shape. The juxtaposition of cloud updrafts (LWC restoration in clouds with surrounding downdrafts leads to a drop in evaporation) may have led to a steep transition zone in the cloud edges. This juxtaposition fostered the formation of very steep gradients between clouds and their close surroundings. The competition between the updrafts microphysical effects and the subsiding shells surrounding the clouds resulted in the trapezoidal shape of the LWC profile along the passes. Further investigations are required to explain LWC and N_c profiles' formation along the traverses.

In the following subsection, we present a quantitative analysis of the clouds' microphysical characteristics.

b. Microphysical parameters and DSDs in zones of intense updrafts (cloud cores)

The main microphysical properties of clouds within the zones of intense updrafts (mostly, cloud cores) can be summarized as follows:

- 1) In CO-I, there were significant small-scale fluctuations in both N_c and LWC. However, at the larger scale of the entire updraft region, these quantities presented significant

uniformity with average values and standard deviations of $N_c \cong 407 \pm 25 \text{ cm}^{-3}$ and $\text{LWC} \cong 2.60 \pm 0.17 \text{ g m}^{-3}$. The length of this homogeneous zone was nearly 400 m.

Within the most intense zones of updrafts ($W = 8.91 \text{ m s}^{-1}$), the sizes of most droplets were within the diameter (D) range of 10–35 μm. These DSDs were narrow, with their maximum diameter at $D = 25 \text{ μm}$, $\sigma \cong 5 \text{ μm}$, and with few small cloud droplets. Examples of such DSDs are shown in Fig. 4a. The narrow DSDs could be attributed to a diffusion growth (i.e., condensation) process of droplets ascending from the cloud base. Pinsky and Khain (2002) showed, using a 2000-bin parcel model, that the stage of pure diffusional droplet growth is short, and the diffusion–collision regime starts fostering the formation of the largest cloud droplets. The tail of the DSD was truncated at $D \sim 37 \text{ μm}$. The largest droplets in the DSD are likely the result of droplet–droplet collisions. Some DSDs found close to the cloud edges were comparable to those found in the cloud core (marked by blue arrow in Fig. 1a and blue curve in Fig. 4a). These DSDs are characterized by high LWC and N_c . All these DSDs are likely the result of droplets nucleated near the cloud base that grew by diffusion within the thicker cloud layer, above which a relatively small number of droplets nucleate. LES simulations (e.g., Khain et al. 2012; Eytan et al. 2019) showed that the updraft ascending from the

FIG. 3. As in Fig. 1, but for CO-III. Arrows point at locations for which DSDs are plotted in Figs. 4c,d.

cloud base might split into several branches (bubbles) at some distance above the cloud base while preserving the parent air properties. It is likely that the DSDs discussed above belong to such bubbles. Note that some such bubbles might turn out to be comparatively close to the cloud edges.

The number concentration of small droplets with $D < 10 \mu\text{m}$ was low including in the cloud cores with strong updrafts. Such small droplets have likely formed by in-cloud nucleation at levels relatively close to those of the aircraft traverse.

- 1) In the updraft region of CO-II, we observed uniform DSD properties within DCC ranging between about -0.40 and 0.0 km (Fig. 2a). The DSDs found in the intense updraft region were relatively narrow (see red arrow in Figs. 2a and 4b). These DSDs had a modal diameter of around $21 \mu\text{m}$ with a relatively small number of small and large droplets. These DSDs were consistent with the narrow DSDs observed in the intense updrafts in CO-I. The lower modal diameter could be attributed to the lower altitude of pass CO-II compared to CO-I.
- 2) In the intense updraft region of CO-III, the DSDs were narrow (see Fig. 3a, and red and black colors in Figs. 4c and 4d), mostly within the diameter range of $15\text{--}30 \mu\text{m}$, with modal D of $15\text{--}16 \mu\text{m}$. There were no (or only very few) small cloud droplets of $D < 12 \mu\text{m}$ in the DSDs in the

updraft region. As was mentioned above, the in-cloud nucleation mechanism was observed and simulated in several studies.

Since mixing decreases buoyancy and reduces updrafts, the existence of strong updrafts zones is an indication that mixing was limited within them (as noted from the LWC and N_c measurements). The usually referred mixing types, such as homogeneous and inhomogeneous, differ in their evaporation rates. These types are indistinguishable in the absence of evaporation, as is the case in clouds. The mixing, referred to as mechanical mixing, becomes similar to passive scalar mixing.

Under these conditions, *DSDs in the zones of strong updrafts (cloud cores) typically have similar shapes*. Thus, mixing in zones of strong updrafts hardly affects the DSD shape. This shape similarity corresponds to relatively homogeneous spatial distributions of LWC and N_c within the cloud bulk. Mechanical mixing (like mixing of passive scalars), performed by large vortices of supposedly convective size, might be a reason for such homogeneity.

c. Microphysical parameters and DSDs in the transition zones

We summarize below the main microphysical properties of clouds in the transition zones:

FIG. 4. Examples of DSDs in (a) CO-I, (b) CO-II, and (c), (d) CO-III at different DCC updrafts and weak downdrafts; CO-III is to the left of the cloud core (DCC ≤ 0) in (c) and CO-III is to the right of the cloud core (DCC > 0) in (d). Locations for which the DSDs are plotted are denoted by arrows in Figs. 1–3.

- (i) Transition zones are more affected by entrainment and mixing with the surroundings than cloud cores. Accordingly, the average LWC and the LWC/LWC_{ad} ratio are lower than in the cores. Sharp jumps in the parameters within widths of ten to a few tens of meters are possible in the transition zones. These jumps are possibly related to the penetration of air filaments (volumes) from the surrounding air. An example of DSD in the transition zone in CO-I is shown in Fig. 4a (yellow curve). The DSD has a wide tail of small droplet formation, probably because of mixing with diluted volumes.
- (ii) A sharp decrease in W with the increase in DCC toward the right-hand side in CO-II, with subsequent upwelling cloud motion, gave rise to considerable variability in r_e , N_c , and LWC values. One such zone of high gradients is shown in Figs. 2a and 2b (black arrow). An example of DSD in the transition zone (DCC = 0.08 km) is shown in Fig. 4b (black line). The modal D (peak of the DSD curve) was 20 μm , with a wide DSD that contained very small-sized droplets with $D < 6 \mu\text{m}$ and large droplets of $D > 30 \mu\text{m}$. The secondary peak around $D = 11 \mu\text{m}$ indicates a multimodal DSD. Since W was relatively small at DCC = 0.08 km, the appearance of the smallest droplet mode was likely the result of mixing with dry-air volumes.

High measurement frequency allows the observation of such a process within small cloud volumes while separating the effect of DSD broadening from that of horizontal averaging. Low measurement frequency may distort the real DSD shape (Korolev 1994; Levin et al. 1996).

- (iii) Transition zones in CO-III also contained sudden fluctuations in W , N_c , and LWC (Fig. 3). DSDs in the zones of such fluctuations are shown in Figs. 4c and 4d. These DSDs had a peak at $D \approx 15 \mu\text{m}$. Due to the appearance of both small and large droplets, we suggest that the DSDs in the transition zones may have been bimodal or multimodal, and the result of mixing between volumes with different histories. New volumes that have recently penetrated the cloud typically contain small droplets. Initially, cloudy volumes contain large drops, with some small droplets that appear there due to partial droplet evaporation and after mixing with the fresh surrounding air. Cloud volumes that did not experience mixing with volumes that have other DSDs might remain unimodal. The formation of such DSDs was described by Khain et al. (2018). It is also possible that the nucleation of new droplets also played a role in zones with positive vertical velocities.

d. Microphysical parameters and DSDs at the cloud edges

The DSD properties at the periphery of the cloud edges showed rapid changes in CO-I, rather than the gradual changes seen when cloud air meets the surrounding air mass. For example, the values of N_c at the cloud edge located on the left-hand side (LHS) of the cloud core decreased from 305 to 0 cm^{-3} within a distance of a few meters. The values of N_c decreased from 428 to 0 cm^{-3} over a distance of about 20 m at the cloud edge along the right-hand side of the core. Examples

of DSDs near the cloud edges are shown in Fig. 4a (purple and green curves). DSD at a DCC of ~ 0.38 km contained both small and large-size cloud droplets; in contrast, the DSD at a DCC of ~ 0.40 km consisted of small evaporating cloud droplets due to the mixing with the surrounding dry air mass. Thus, the DSD changed dramatically over distances of just 20 m. The widths of these zones (mostly 10–20 m) were also reported in the RICO experiment, following high-frequency measurements in small Cu (Gerber et al. 2008).

Near the cloud edges in CO-II (see Figs. 2 and 4b) and CO-III (Fig. 3), σ showed considerable variability, which indicates the presence of both narrow and wide DSDs. The DSDs near the cloud edges were characterized by elongated tails of small droplets and the appearance of several DSD modes (see Figs. 4c,d).

DSDs near the cloud edges were measured in a diluted volume, with the LWC being about twice as low as at the cloud maximum. One can see that the existence of a tail of small droplets caused the wide DSD. The main DSD peak was much smaller, and the DSD shifted toward small sizes compared to the narrow DSDs of the cloud core. However, note that the change in the largest drops' radii was smaller than that of the smaller droplets. As a result, the decrease in r_e , which is determined mainly by the large droplets, was smaller than that in LWC and N_c across clouds and even near the cloud edges. A similar change in the shape of DSDs near the cloud edges was measured by Kumar et al. (2017) and simulated by Pinsky et al. (2016a,b) and Pinsky and Khain (2018b).

High DSD shape variability near the cloud edges could be attributed to different histories of air volumes at the cloud periphery. Volumes that recently entrained into the cloud likely contain small droplets because of the initial low RH and intense droplet evaporation. In contrast, volumes or parcels of air arriving from the interior of the cloud and mixing briefly with drier parcels of air would contain both small and large droplets.

The entrainment might lead to the penetration of some cloud nuclei into the updraft zones. These cloud nuclei can be activated to droplets and grow in the updrafts. In our case study, however, the flights were performed at high altitudes, where the concentration of aerosols was expected to be low, so no nucleation of droplets from the CCN penetrating into cloud is expected.

e. Analysis of DSD properties

1) VARIATIONS IN DROPLET CONCENTRATIONS WITHIN THE DIFFERENT SIZE RANGES

The mechanism of DSDs formation can be better understood by comparing the concentrations of droplets of different sizes. We calculated droplet concentrations along the cloud transect in the following diameter ranges: small ($2 \leq D \leq 10.50 \mu\text{m}$), medium ($10.50 < D \leq 19 \mu\text{m}$), and large ($19 < D \leq 50 \mu\text{m}$; Fig. 5). The concentration of large droplets was greater than smaller ones in CO-I and CO-II, while large and midsize droplet concentrations were of the same order of magnitude in CO-III. In all three cases, transition zones with low W and zones at the cloud periphery contained more of the smallest

droplets, whereas the updrafts contained the highest concentration of large drops. This finding agrees with the results of Khain et al. (2013), who showed efficient large droplets formation in the slightly diluted cloud regions.

(i) Droplet concentrations in CO-I

The small N_c variations in the updraft zones indicate either that these zones are slightly diluted and/or that the clouds are well mixed horizontally. The N_c of large droplets in CO-I was consistently high ($>300 \text{ cm}^{-3}$) while N_c of small size droplets was less. This may indicate that evaporations of large cloud droplets were yet to take place through mixing with dry air.

(ii) Droplet concentrations in CO-II

The concentration of large droplets in CO-II was higher than the other two droplet size ranges. However, along the right-hand side of the transition zone (see Figs. 2a and 5b), the increase in small- and medium-sized droplet concentrations corresponded to a decrease in large droplet concentration. In this transition zone, the large droplets have probably partially evaporated, contributing to an increase in N_c of the small- and medium-sized droplets. Interestingly, in the transition zone in the left part of the path, a decrease in large droplet concentration corresponded to an increase in the concentration of medium-sized droplets, while concentration of the small droplets increased only slightly. The difference in the DSD shapes, especially near the cloud edges, is not surprising given the considerable variability in the DSDs in this region.

(iii) Droplet concentrations in CO-III

In CO-III, the concentration of medium-sized droplets was higher than of the other two droplet size ranges. This can be attributed (at least partially) to the low flight elevation in this case so that the number of large drops forming under the influence of droplet collisions is smaller than in the other flights. At the extreme edges of the downdraft zone, an increase in N_c of large cloud droplets was noted (DCC = 1.7 km, Fig. 5c). These droplets may have remained from a previous history of growth in cloud updrafts. Different histories of droplets determine large variations in DSD widths and other DSD parameters within the downdraft zone at the cloud edges. The scenarios of the DSD formation at the cloud edges were considered above.

2) RELATIONSHIP BETWEEN LWC AND N_c

Statistics describing the relationship between the LWC of the large droplets ($19 < D < 50 \mu\text{m}$) and the N_c of the small droplets ($2 < D < 10.50 \mu\text{m}$) for the three traverses are illustrated by scatterplots in Fig. 6. One can see that the maximal LWC values of the large droplets (which determine the total LWC) were reached near the zone of maximal updrafts and corresponded to a low concentration of small droplets. As discussed above, these small droplets have likely arisen from the in-cloud nucleation. The minimum LWC values of large droplets typically correspond to a higher concentration of small droplets as a result of mixing and drop evaporation at the cloud periphery. There were, however, exceptions: near the cloud edges in CO-II and CO-III (see Figs. 6b,c), an increase in

FIG. 5. Observation at 25-Hz resolution of cloud droplet number concentrations in different size (diameter D) ranges: $2 < D < 10.50 \mu\text{m}$ (small), $10.50 < D < 19 \mu\text{m}$ (medium), and $19 < D < 50 \mu\text{m}$ (large). Vertical velocity (W , m s^{-1}) was measured at a resolution of 1 Hz. (a) CO-I, (b) CO-II, and (c) CO-III.

N_c ($2 < D < 10.50 \mu\text{m}$) to high values was not accompanied by a decrease in LWC of large droplets. These zones correspond to the cloud edges where there is high DSD shape variability.

Figure 7 shows a scattering diagram of large droplets N_c ($19 < D < 50 \mu\text{m}$) against $\text{LWC}/\text{LWC}_{\text{max}}$. It reveals that the LWC increased linearly with the increase in large droplets N_c . This linearity is often interpreted as evidence for extreme

inhomogeneous mixing because it corresponds to a constant mean volume and r_e . However, as we mentioned above, the RH inside clouds is $\sim 100\%$, in which case the mixing types are indistinguishable because the mixing is not accompanied by evaporation. The mixing is close to a mechanical mixing between passive scalars. The linearity means that most of the droplet mass was concentrated in the large drops. However,

FIG. 6. Scatterplots: LWC of large droplets ($19 < D < 50 \mu\text{m}$) vs the number concentration (N_c) of small droplets ($2 < D < 10.50 \mu\text{m}$) for (a) CO-I, (b) CO-II, and (c) CO-III. The colors indicate the cluster numbers: cluster I ($0.75 < \text{LWC}/\text{LWC}_{\text{max}} < 1$), cluster II ($0.3 < \text{LWC}/\text{LWC}_{\text{max}} < 0.75$), and cluster III ($0.01 < \text{LWC}/\text{LWC}_{\text{max}} < 0.3$).

this linearity breaks down in the downdrafts of CO-III, primarily at the cloud periphery, where evaporation was efficient. Note that the curvature indicates a faster decrease in the concentration than the mass of large droplets. From a physical point of view, such dependence can be explained by the fact that the mass is concentrated in the largest droplets, so complete evaporation of the smallest droplets does not change the LWC in the same proportion. Note that partial evaporation in CO-III led to a decrease in the concentration of large droplets, so that, at $\text{LWC}/\text{LWC}_{\text{max}} < 0.2$, the entire mass was concentrated in droplets with $D < 19 \mu\text{m}$.

A scattering diagram of small droplet concentration N_c ($2 < D < 10.50 \mu\text{m}$) against $\text{LWC}/\text{LWC}_{\text{max}}$ is shown in Fig. 8. A very low concentration of small droplets was present in zones of high LWC. As mentioned above, small droplets existed in the diluted regions near the cloud edges, especially in the downdraft regions.

f. Mixing diagrams

The mixing characteristics are often illustrated using mixing diagrams that show the relationship of the cube of normalized r_e versus normalized LWC or droplet concentration (e.g., Burnet and Brenguier 2007; Gerber et al. 2008; Lehmann et al. 2009; Pinsky and Khain 2018a). The physical meaning of such diagrams and their relation to the mixing process were discussed by Khain et al. (2018), who studied a scatter diagram of $(r_e/r_{e,\text{max}})^3$ versus $N_c/N_{c,\text{max}}$ in a Lagrangian–Eulerian cloud model by following the trajectories of interacting air volumes. Although the observations do not allow us to follow cloud volumes, we plotted scatter diagrams of $(r_e/r_{e,\text{max}})^3$ versus $\text{LWC}/\text{LWC}_{\text{max}}$ (Figs. 9a,c,e). As discussed above, the values of $\text{LWC}/\text{LWC}_{\text{max}}$ were separated into three ranges referred to as “clusters.” Most measurements in CO-I were related to cluster I (Fig. 9a). As we saw in Fig. 1, the r_e in cluster I was nearly uniform along the path. The smallest values of r_e occurred at the cloud edges, where the DSDs were as shown in Fig. 4a.

In cluster I, the values of $(r_e/r_{e,\text{max}})^3$ versus $\text{LWC}/\text{LWC}_{\text{max}}$ in CO-II and CO-III were similar to those in CO-I. These clouds have the cloud core with the strongest updrafts. Toward the cloud edge, r_e decreased with $\text{LWC}/\text{LWC}_{\text{max}}$. In clusters II and III (Figs. 9c,e), a significant drop in $(r_e/r_{e,\text{max}})^3$ took place in CO-II and CO-III. In these zones, the DSDs are shifted toward droplets of the smaller size. Smaller values of r_e indicated the existence of a significant number of air volumes (DSDs) that do not contain any or contain only a small number of large droplets. Similar behavior was observed by Gerber et al. (2008) during certain flights (see their Fig. 8). The DSD shift toward smaller droplet sizes could be due to partial evaporation during mixing (Pinsky et al. 2016a,b) and partial evaporation in downdrafts, where SS is negative (Pinsky and Khain 2019c). Note that zones with small $(r_e/r_{e,\text{max}})^3$ are narrow and are not resolved in measurements performed with a resolution of 1 Hz (100 m), which is why they were not reported. Again, note that maximum r_e occurred in zones of high LWC, that is, zones of updrafts. These conditions are favorable for drizzle and raindrops formation.

The scatter diagrams of σ versus $\text{LWC}/\text{LWC}_{\text{max}}$ are shown in Figs. 9b, 9d, and 9f. A wide DSD indicates that both small

FIG. 7. Scatterplot of the number concentration (N_c) of large drops ($19 < D < 50 \mu\text{m}$) vs $\text{LWC}/\text{LWC}_{\text{max}}$. (a),(c),(e) The color bars show cluster I ($0.75 < \text{LWC}/\text{LWC}_{\text{max}} < 1$), cluster II ($0.3 < \text{LWC}/\text{LWC}_{\text{max}} < 0.75$), and cluster III ($0.01 < \text{LWC}/\text{LWC}_{\text{max}} < 0.3$). (b),(d),(f) Color bars show the vertical velocity (W , m s^{-1}) in the three clusters.

and large droplets were included, resulting in a broad spectrum. In CO-I and CO-II, the smallest σ values (narrow DSD) were found in the slightly diluted regions (cluster I). The maximum scatter in σ was found in cluster II, indicating a large variability in DSD widths. These DSDs belong to the transition zone. In cluster III, there were cloud volumes with large tails of

small droplets and volumes of dry air containing only the smallest droplets and thus a narrow DSD (e.g., small σ and r_e values).

Many volumes in cluster III have penetrated from the surroundings and contained only small droplets and thus narrow DSDs. The presence of such volumes decreased the averaged

FIG. 8. As in Fig. 7, but for N_c of small droplets ($2 < D < 10.50 \mu\text{m}$) vs $\text{LWC}/\text{LWC}_{\text{max}}$.

DSD width in cluster III. The maximum DSD width occurred at intermediate LWC values, where both small and large droplets were present.

Therefore, there were two types of narrow DSDs in CO-III: in case of high LWC, the DSDs contained large droplets formed in updrafts ascending from the cloud base in slightly diluted cores; in case of low LWC observed at the periphery of the transition zone, where many recently penetrated air volumes with low RH or with only small droplets could be found.

The in situ data allow us to determine the relationships between $\text{LWC}/\text{LWC}_{\text{max}}$ and relative dispersion. Figure 10 shows a scatter diagram of ε versus $\text{LWC}/\text{LWC}_{\text{max}}$. One can see that ε increases as LWC decreases in the cloud parcels. The smallest values of ε were for slightly diluted cloud parcels where the DSDs are narrow. One can see that, for cloud cores, the relative dispersion was about 0.36, a typical value for Cu (Politovich 1993; Khain and Pinsky 2018).

FIG. 9. Scatter diagrams of $(r_e/r_{e_{max}})^3$ or the spectral width (σ , μm) vs LWC/LWC_{max} for (a),(b) CO-I, (c),(d) CO-II, and (e),(f) CO-III. The color bars show the cluster numbers.

FIG. 10. Relationship between relative dispersion (ϵ) and normalized LWC plotted together for CO-I, CO-II, and CO-III. CC is the correlation coefficient, and p is the significance level.

g. Spectral and correlation properties of LWC and N_c

The high-resolution data allow us to investigate the spectral characteristics of LWC and related mixing processes. Figures 11 and 12 show the power spectra of LWC and N_c plotted using high-resolution data. We found that LWC and N_c power spectrum fluctuations obeyed the $-5/3$ law in all three cloud paths. The velocity power spectrum in homogeneous and isotropic turbulence also obeyed the $-5/3$ law. MacPherson and Isaac (1977) showed that the velocity turbulent power spectra obey the $-5/3$ law within the range of 10–1000 m. It is known that the power spectrum of passive scalar within such a turbulent flow also obeys the $-5/3$ law (Obukhov 1949; Corrsin 1951; Sreenivasan 1996). Note that LWC and N_c are not passive scalars because they have sources or sinks within clouds. Nevertheless, Gerber (2000) and Gerber et al. (2001) reported the $-5/3$ power spectrum of LWC in shallow Cu. They found a deviation from the $-5/3$ law only at scales smaller than several meters. Such small scales are not resolved in the measurements discussed in the present study. Pinsky and Khain (2003) calculated power spectra of drop concentration fluctuation in small Cu, with findings similar to the LWC power spectra in Gerber (2000) and Gerber et al. (2001). Deviation from the $-5/3$ law at scales below 5 m is attributed in the above studies to turbulent diffusion of initially existing inhomogeneity due to cloud boundaries, entrainment processes, and more. This inhomogeneity leads to an increase in amplitude and a decrease in spatial scale. A plausible explanation for LWC and N_c being nonpassive scalars that obey the $-5/3$ law is that these variables do not change significantly at turbulent fluctuation scales. Note that there exist small-scale (~ 1 cm) fluctuations of these parameters (so-called droplet clustering) because of turbulent effects and drop inertia. Such fluctuations affect the collision

FIG. 11. Power spectra of LWC vs wavenumber, plotted for (a) CO-I, (b) CO-II, and (c) CO-III. The straight black lines show the $-5/3$ slope.

FIG. 12. Power spectra of number concentration (N_c), plotted for (a) CO-I, (b) CO-II, and (c) CO-III. The straight black lines show the $-5/3$ slope.

rate but cannot be observed in 25 Hz measurements. A detailed analysis of the formation mechanisms of nonpassive variable power spectra in a turbulent flow is beyond the scope of the study.

Figure 13 shows normalized horizontal autocorrelation functions of LWC and N_c for all cloud traverses. In CO-I and CO-II, the autocorrelation functions fell to zero or a small value slightly depending on the distance at about 20–40 m, known as the radius of correlation. It means that the values were highly correlated at this spatial scale. In other words, these spatial points located at distances below ~ 25 m were within the same vortex. Accordingly, the size of the turbulent vortices at which N_c as well as LWC values were correlated was below or about ~ 25 m. Outside this range, the values were not correlated.

Typically, radius of correlation of microphysical variables is related to the radius of correlation of vertical velocities. However, the radii of correlation of different microphysical variables can be different (see Magaritz-Ronen et al. 2014). Typically, radius of correlation of N_c is lower than that of LWC, because of higher variability of N_c . Indeed, N_c can change due to droplet nucleation or evaporation of small droplets. These processes may lead to significant changes in N_c , but to much lower changes of LWC. This difference is well seen in CO-II. As regards to CO-III radii of correlation of N_c and LWC are similar ~ 40 m. Larger statistics is required to determine correlation radii with the higher precision.

The autocorrelation functions indicate some oscillations up to about 120–175 m. These scales indicate the sizes of the largest vortices, close to the external turbulent scale, which depend on the cloud size. However, in case of CO-III, the autocorrelation does not cross the x axis because of the presence of large-scale (cloud scale) curvature of the profile $N_c(x)$. Thus, it was impossible to choose the stationary segment of large enough length. However, rapid decrease of the function at the first 25 m is obvious, which again shows the characteristic size of turbulent vortices. There are also indications of the presence of large-scale vortices (filaments) of about 50–175 m. According to Grabowski and Clark (1991, 1993), the maximum scale is about a tenth of the cloud size. Vortices of larger sizes possibly exist in convective clouds. We suppose that they are of convective nature and are responsible, for instance, for the increase in mass flux with height occurring in clouds. Note that the LWC crossed the x axis at nearly $x = 40$ m but N_c does not, which may be due to the reason that LWC values in CO-III are contributed by smaller cloud droplets. Since LWC is proportional to D^3 , such an out-of-phase relationship between N_c and LWC is expected. In CO-I and CO-II, the LWC values were contributed by large cloud droplets that yield increased LWC with N_c and thus the variations of both N_c and LWC were more coherent. More extensive statistics, detailed analysis, and a comparison with high-resolution LES are required to better understand the turbulent properties of microphysical variables.

5. Discussion and conclusions

The entrainment and mixing processes play crucial roles in cumulus cloud interactions with the surroundings and affect

FIG. 13. Normalized autocorrelation functions of LWC and N_c in the updraft regions for (a) CO-I, (b) CO-II, and (c) CO-III.

cloud microphysics, drizzle and raindrop formation, cloud life time, and cloud cover. Strong gradients in microphysical variables exist at the cloud edges; these interface zones between clouds and their surroundings might have a width of only a few

tens of meters. Typical 1-Hz measurements of microphysical quantities have a spatial resolution of about 100 m, which is too crude to investigate the transition-zone microphysics or determine cloud edge parameters. Moreover, 1-Hz measurements do not permit the investigation of turbulent structures in clouds and turbulence impact on cloud microphysics. Several studies have analyzed the results of higher-frequency measurements (up to 1000 Hz, Gerber 2000); these studies typically considered the general properties of small Cu, so a detailed analysis of cloud microphysics in deep cumulus is warranted.

In the present study, we analyzed 25-Hz in situ observations in deep convective clouds during CAIPEEX-2015, focusing on detailed cloud microphysics. The entrainment and mixing processes were investigated along with vertical velocities and DSD properties, and cloud parcels were classified based on the key findings of the analysis. We considered three traverses, CO-I, CO-II, and CO-III, through growing clouds at different altitudes above the cloud base. The traverses had substantially different lengths, from a few hundred meters in CO-I to ~3 km in CO-III. CO-III represents a cross section of the cloud with a strong updraft in the middle, subsiding shells near the cloud edges, and a broad transition zone of weak updrafts.

Analysis of microphysical parameters and DSDs in the three cloud traverses led us to the following conclusions about the cloud microphysical properties:

- 1) Zones of high W are characterized by high LWC and N_c values. These zones are slightly diluted.
- 2) Droplets reach their maximum size within zones of strong updrafts. The droplets most likely arise near the cloud base by aerosol nucleation and then grow by diffusion in updrafts. A combination of high N_c and LWC in the zone of strong updrafts indicates that the first drizzle and raindrops may arise in this slightly dilution zone. The DSDs were narrow and similar in their shape, and contained no or very few small droplets, which might indicate that droplets have already grown to larger drops and that there was lower evaporation or generation of new drops. The secondary modes formed by the smaller droplets were considered with the main DSD mode (due to their rapid growth) and, thus, the DSDs could be considered unimodal. These DSDs had low variability within this zone.
- 3) In the transition zones, the DSD typically broadens due to the appearance of small droplets. Both the DSD width and relative dispersion increased in this zone.
- 4) Depending on their history, several DSD modes could be found at the cloud edges and in the transition zones. They could be broad, containing both large and small droplets (such DSDs correspond to relatively high LWC), or they could contain only small droplets (such DSDs correspond to low LWC). DSDs containing small droplets were likely found in air volumes that have recently penetrated already existing clouds. These are often highly diluted, so most of the droplets evaporate, leaving behind only previously large droplets still undergoing evaporation. Such a DSD has low width but high relative dispersion. As a result, the DSD widths in the moderate and, especially strongly diluted zones can have high variability.

- 5) At “large cloud scales,” changes in LWC and N_c within slightly diluted updrafts were minor. The values of $LWC_{\max}$ were about 0.7–0.8 of LWC_{ad} . The decrease in LWC could result from the breaking of ascending cloud volumes into separate smaller volumes. This could happen due to turbulence diffusion or in-cloud mixing, including “large scale” nonlocal mixing (the entrainment of a mass by convective-scale motions). This indicates that in-cloud dynamics are a crucial component affecting DSD behavior. Consequently, the LWC in clouds had a trapezoidal shape with steep gradients near the cloud edges. Such steep gradients could be attributed to the fact that the surrounding air was affected by short-term mixing during the cloud developmental stage. Additionally, the formation of a subsiding shell in which cold and dry air descend along the cloud edges could also foster the steep gradients.
- 6) In some cases, volumes with high LWC were located within the transition zone and even near the cloud edges. We found that large droplets sometimes appeared very close to the cloud edges in slightly diluted volumes in the presence of strong updrafts. This was most likely a result of a horizontal mixing with the volumes ascending from the cloud base and turning out close to the cloud edges. High-resolution LESs of Cu showed that zones of high LWC could break into several zones, some of which could be shifted toward the cloud edges by horizontal velocity components (Eytan et al. 2019). Experimentally, these DSDs could only be found in high-resolution data. In the absence of history of moving cloud volumes, we were unable to analyze this effect further.
- 7) The effective (or mean volume) radii show much lower variability than N_c and LWC. Since the mean volume radius is the cubic root of the ratio of LWC/N_c , it is clear that LWC and N_c are well correlated. Consequently, modal radii and, especially, effective radii changed (horizontally) by only a few microns within cloud updraft zones. This uniformity in radii is found despite significant changes in the W and rate of dilution. Since the adiabatic profile $LWC_{\text{ad}}(z)$ is depended only on the conditions on the cloud base, the profiles of $r_e(z)$ turn out to be dependent on the droplet concentration or even on aerosol concentration in the boundary layer only (here, z indicates the cloud depth of a cloud). This means that nonprecipitating developing clouds can be characterized by a “universal” profile of an effective radius if undiluted or slightly diluted core exists. This result can be used in the microphysics parameterization of nonprecipitating clouds.
- 8) The value of r_e decreased with a decrease in LWC at the cloud periphery, especially in downdrafts. This effect could be attributed to the shift in DSDs toward smaller droplet sizes, which is especially strong in downdraft zones.
- 9) The power spectra of LWC and N_c obeyed (in general) the $-5/3$ turbulence law, likely showing that the mixing and entrainment at least at small scales are of a turbulent nature.
- 10) Autocorrelation functions show that LWC and N_c correlation radius in the zone of cloud updraft was 20–40 m. The turbulent external scale or scale of large vortices was estimated at 120–175 m.
- 11) Most of the results presented in this study, including the cloud properties near the edges and other regimes, and the power spectra, were achieved only because high-frequency measurements were taken.

Clearly, current sampling techniques presented here cannot delve into the three-dimensional spatial characteristics of cloud dynamics and microphysics. More detailed statistical analysis, combined with DNS and LES, is required to evaluate the external turbulence scale, understand the reasons for the deviation of LWC and N_c spectra from the $-5/3$ law within slightly diluted zones, evaluate changes in the dominating scale of turbulent fluctuations along cloud traverses, evaluate the role of subsiding shells in the process of entrainment and mixing, and other questions.

In this study, we focused on developing clouds. Analysis of the mature and decaying stages of cloud evolution is essential for comprehending the effects of clouds on their close surroundings. It is worth noting the high sensitivity of GCMs to the ways of describing microphysical processes that hinders the parameterization of the contribution of heating/cooling and wetting/drying due to the clouds. We hope that the cloud microphysical processes described here will benefit such studies.

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