

RESEARCH ARTICLE

Characteristics of upper-level updrafts and downdrafts in the anvils of tropical deep convective clouds

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Abstract

This study examines thermodynamic and microphysical relationships between in-cloud updrafts and downdrafts within tropical deep convective anvil clouds, using aircraft in situ measurements from the Aerosol, Cloud, Precipitation, and Radiation Interactions and Dynamics of Convective Cloud Systems–Cloud Processes of the Main Precipitation Systems in Brazil (ACRIDICON–CHUVA) field campaign. Our results extend current knowledge of in-cloud drafts to higher altitudes and add detail regarding their microphysical characteristics. Key findings include observational evidence of supersaturated downdrafts and higher cloud particle number concentrations in downdrafts than in updrafts within optically thick anvil clouds. Mean draft diameters exhibit a broadening trend with altitude, while mean air-mass fluxes decrease due to decreasing vertical velocity intensity and atmospheric density. Cloud water content is comparable in up- and downdrafts and increases with vertical velocity at all levels, without a clear trend with altitude. At upper levels (10–14 km), large negative vertical velocities ($w < -2 \text{ m} \cdot \text{s}^{-1}$) are observed in supersaturated regions ($\text{RH}_{\text{ice}} > 110\%$); therefore, upper-level downdrafts do not appear to be driven by latent cooling. Optically thick cloud regions exhibit higher median RH_{ice} and ice water content (IWC) compared with optically thin clouds, with downdrafts ($w < -0.5 \text{ m} \cdot \text{s}^{-1}$) showing higher median RH_{ice} and IWC than updrafts. Particle size distributions are similar for up- and downdrafts of comparable strength. With altitude, maximum particle size increases, and the number concentration of larger particles ($> 100 \mu\text{m}$) increases more strongly in stronger drafts than in weaker drafts. Stronger drafts also exhibit higher concentrations of particles smaller than $100 \mu\text{m}$ at upper levels. Optically thick regions exhibit higher particle number concentrations across all sizes than optically thin regions. Notably, within the optically thick regions, downdrafts show higher particle number concentrations than updrafts for all sizes. Overall, the characteristics of updrafts and downdrafts in anvil clouds exhibit strong similarities, suggesting the influence of processes, such as updraft–downdraft mixing and inertia-driven downdrafts originating from older updraft cores, shaping microphysical and dynamical properties of anvil clouds.

KEYWORDS

cloud microphysics and dynamics, downdrafts, tropical anvil clouds, updrafts

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1 | INTRODUCTION

Deep convective clouds (DCCs) contribute up to 75% of tropical rainfall (Roca *et al.*, 2014). Vertical motion in DCCs through updrafts and downdrafts couples the boundary layer with the free troposphere, facilitating the transport of mass, water, energy, aerosols, and pollutants from the boundary layer to the mid and upper troposphere (Barth *et al.*, 2015; Cotton *et al.*, 1995). These clouds also bring free tropospheric properties to near-surface areas (Betts, 1976; Zipser, 1977) and, in the upper cloud levels, can enable transport from the stratosphere to the troposphere (Frey *et al.*, 2014) and vice versa. The structure of a DCC has two major parts: the convective core and the anvil (Machado & Rossow, 1993). While the convective core of a DCC produces heavier rainfall (Leary & Houze, 1979) and contributes to the majority of the rainfall (Houze, 1977), the anvil spreads horizontally and persists longer, thus influencing the radiative feedback by reflecting incoming shortwave (SW) radiation and trapping outgoing longwave (LW) radiation. The frequency of high-level cirrus clouds, including anvil cirrus, reaches up to 70% in certain longitudinal bands over the Tropics (Nazaryan *et al.*, 2008; Sassen *et al.*, 2009), and anvil clouds comprise up to 80% of a mature convective system in terms of horizontal extent (Machado & Rossow, 1993). Notably, anvil cloud feedback is one of the primary sources of uncertainties in current regional-scale (e.g., Cronin & Romps, 2020; Singh and O’Gorman, 2015; Wing, 2017) and global-scale numerical models (e.g., Narenpitak *et al.*, 2017; Tsushima *et al.*, 2014).

Convective updrafts are initiated through buoyancy forces generated by turbulent transport of heat and moisture, shear, convergence, or orographic lifting, and maintained through the release of latent heat during condensation and freezing processes (Grabowski & Morrison, 2021; McMurdie & Houze, 2006). The downward drag force from hydrometeor loading initiates convective downdrafts and is maintained by latent cooling from evaporation, melting, and sublimation (Knupp & Cotton, 1985; Wang *et al.*, 2022). The current viewpoint of these draft characteristics is based predominantly on observations from lower-altitude convective core regions (e.g., Giangrande *et al.*, 2013; LeMone & Zipser, 1980; Yang *et al.*, 2016a), as earlier campaigns were aimed towards probing the most active parts of the convection using both in situ aircraft and remote sensing measurements. These relationships may change in ice clouds compared with warm or mixed-phase clouds in the lower levels due to added complexities, such as different ice-crystal shapes. The microphysical properties can differ between updrafts and downdrafts as a consequence of the distinct thermodynamic conditions favoured by each. For instance, updrafts are characterised by supersaturated conditions (Grant *et al.*, 2022),

leading to cloud particle nucleation and growth, whereas downdrafts, in the general view, experience subsaturated environments that favour evaporation and sublimation (Knupp & Cotton, 1985; Pawlowska-Mankiewicz, 1987). Additionally, differences in simulated characteristics of convective updrafts and downdrafts exist in models due to the inaccurate representation of physical processes that drive and maintain them, such as latent heat release due to freezing (Varble *et al.*, 2014) and evaporation (Wang *et al.*, 2022). Accurate characterisation of the microphysical and dynamical properties in upper-level regions is therefore essential. Furthermore, the intercomparison of microphysical properties between updrafts and downdrafts is notably absent in the past literature.

A few studies have probed high altitudes through downward-looking Doppler radar from aircraft (Heymsfield *et al.*, 2010) and ground-based radar wind profilers (Wang *et al.*, 2020), which have helped to establish the baseline vertical motion statistics for convective cores. However, studies focusing on vertical velocity retrieval and the microphysical characteristics of anvil regions, which constitute a dominant part of the deep convective system spatially and temporally, are lacking. Additionally, the inability to retrieve detailed microphysical and thermodynamic properties using remote sensing methods does not provide a complete understanding of the interaction of microphysics with vertical motion. Moreover, validation of vertical velocity retrievals from ground-based remote sensing for upper-cloud regions remains challenging without co-located in situ measurements (e.g., Muhlbauer *et al.*, 2014).

The challenge in understanding upper-level cloud processes stems from the limited availability of comprehensive in situ observations that can capture both dynamical variables (vertical velocity, draft characteristics) and microphysical properties (cloud water content, particle size distributions, thermodynamic conditions) simultaneously. In situ measurements provide direct sampling of microphysical and thermodynamic variables with high temporal resolution and minimal retrieval assumptions. The existing aircraft data have been instrumental in constructing and quantifying thermodynamic and microphysical characterisations of high clouds, including anvil clouds (e.g., Krämer *et al.*, 2016, 2020), while the link to dynamical variables, especially in cloud anvils, remains less explored.

To investigate the relationship between cloud dynamics and microphysics, previous studies have often relied on remote sensing data, such as satellite imagery or radar reflectivity, to provide contextual information on the aircraft position within the cloud system. Correlating in situ measurements with such supporting data is commonly performed manually for case studies, for example,

to determine the life stage and phase of the cloud system (Frey *et al.*, 2014; Jäkel *et al.*, 2017). However, this manual approach restricts the sample size and limits the generalisability of the results. Automated classification methods that can be applied consistently across an entire campaign offer a way to increase sample size and statistical robustness substantially (e.g., Atlas & Bretherton, 2023).

To address these gaps and to gain a deeper understanding of the characteristics of deep convective cloud anvils, this study utilises high-altitude (10–14 km) in situ measurements from the Aerosol, Cloud, Precipitation, and Radiation Interactions and Dynamics of Convective Cloud Systems–Cloud Processes of the Main Precipitation Systems in Brazil (ACRIDICON-CHUVA) campaign over the Amazon (Wendisch *et al.*, 2016). In particular, we quantify the dynamical, thermodynamic, and microphysical properties of updrafts and downdrafts. Using in situ measurements from upper-level anvil regions, we assess whether systematic dynamic and microphysical differences exist between updrafts and downdrafts. Additionally, we use satellite-derived infrared (IR) brightness temperatures to classify cloud regimes by using the temperature difference between brightness temperature and in situ air temperature. With this study, we aim to improve our understanding of convective anvils and provide in situ data to help inform and support process understanding and representation in numerical model simulations. As previous studies focused mostly on the core region of deep convection, this study will provide an addition, highlighting the in-anvil cloud draft characteristics and linking them to cloud microphysics.

The study is organised as follows: Section 2 describes the instruments and dataset used in this study and Section 3 outlines the methodologies employed for data processing. Section 4 first presents the draft statistics, followed by observed differences of microphysical properties in updrafts and downdrafts with different thermodynamic and optical thickness conditions. Section 5 discusses these findings to interpret the physical link between dynamics and microphysics in upper-level updrafts and downdrafts. Finally, Section 6 concludes the study.

2 | DATASET AND INSTRUMENTS

2.1 | ACRIDICON-CHUVA field campaign

This study uses the data from the ACRIDICON-CHUVA flight campaign (Wendisch *et al.*, 2016), which was conducted during the period of September–October, 2014 over Amazonia, Brazil. The campaign aimed to investigate tropical deep convective clouds and precipitation, focusing on

various research topics, including cloud vertical evolution and life cycle, cloud processing of aerosol particles and trace gases (Braga *et al.*, 2021, 2017), and vertical transport and mixing (Cecchini *et al.*, 2017a), employing different flight strategies.

The campaign included 14 research flights with the German High Altitude and Long Range Research Aircraft (HALO) and collected nearly 13 hours of in situ cloud data. The high endurance of the HALO aircraft enabled it to conduct extensive flights, for which it carried sophisticated instruments to obtain in situ dynamical and cloud microphysical observations across regions with varying meteorological conditions. These include rare measurements inside anvil clouds at altitudes up to 15 km.

The combination of microphysical and dynamical measurements provides a unique opportunity to study the complex dynamical–microphysical interactions within the cloud. Here, the focus will be on measurements of vertical velocity (w), cloud water content (CWC), and particle size distributions (PSDs). However, biases in the sampling strategies and flight patterns affect the statistics and may not necessarily reflect the statistics as in nature, particularly at the core of deep convection. Additionally, the observations cannot capture the temporal evolution of cloud properties, providing only instantaneous snapshots of cloud variables and thermodynamic conditions at discrete altitudes. The instruments from which the measurements are retrieved are described briefly below.

2.1.1 | General meteorology and wind measurements

The vertical wind speed (w) measurements and other meteorological and aircraft variables, such as temperature (T), pressure (P), and true air speed (TAS), were obtained from the Basic Halo Measurement and Sensor System (BAHAMAS: Krautstrunk & Giez, 2012) with 1-Hz temporal resolution (standard temporal resolution is 10 Hz). The three-dimensional (3-D) wind measurements were calibrated following Mallaun *et al.* (2015), resulting in an uncertainty of $0.3 \text{ m} \cdot \text{s}^{-1}$ for the horizontal components and $0.2 \text{ m} \cdot \text{s}^{-1}$ for the vertical components. The absolute error values of temperature and static pressure are 0.4 K and 15 Pa, respectively (Giez *et al.*, 2023).

2.1.2 | Relative humidity measurements

The relative humidity with respect to ice (RH_{ice}) is retrieved from the gas-phase mixing ratio of water ($\text{H}_2\text{O}_{\text{gas}}$) measured by the Sophisticated Hygrometer for Atmospheric Research (SHARC), which is a tunable diode laser

(TDL) hygrometer developed at DLR Flight Experiments. It is a closed-cell hygrometer that uses the absorption line of water vapor at $1.37\ \mu\text{m}$. The measurement range is from 5 to 50,000 ppm and the overall uncertainty is 5% relative or ± 1 ppm absolute uncertainty, whichever is larger, with 10 Hz temporal resolution (Giez *et al.*, 2023).

2.1.3 | Cloud particle measurements

The cloud particle sizes and number concentrations are retrieved using the New Ice eXperiment-Cloud and Aerosol Particle Spectrometer (NIXE-CAPS) and provided at 1-Hz temporal resolution. There are two instruments incorporated in NIXE-CAPS: the Cloud and Aerosol Spectrometer with detector for polarisation (NIXE-CAS-DPOL) and the Cloud Imaging Probe greyscale (NIXE-CIPg). The NIXE-CAS-DPOL instrument utilises the light forward-scattered by aerosol particles, water droplets, and ice crystals to determine the particle size of particles between 0.61 and $50\ \mu\text{m}$, based on Mie scattering theory of spherical particles. NIXE-CIPg, an optical array probe, records two-dimensional images of cloud droplets and ice particles in the size range between 15 and $937.5\ \mu\text{m}$, with a resolution of $15\ \mu\text{m}$, using the maximum dimension. On average, both NIXE-CAS-DPOL and NIXE-CIPg instruments exhibit an uncertainty of about 20% in measuring the size of the particles and the number concentrations (Meyer, 2012). Combining NIXE-CAS-DPOL and NIXE-CIPg outputs, particles with diameters between 0.61 and $937.5\ \mu\text{m}$ can be sized and counted in 71 bins to obtain cloud PSDs. We use PSDs from Krämer *et al.* (2025a) with 30 bins.

2.2 | Brightness-temperature data

The National Centers for Environmental Prediction/Climate Prediction Center Level 3 Merged Infrared Brightness Temperature dataset is a globally merged product from multiple geostationary satellites (Janowiak *et al.*, 2017). This dataset provides brightness temperatures (T_b) at 4-km spatial resolution and half-hourly temporal resolution in the latitude band 60°S – 60°N .

3 | METHODS

This section outlines the methodologies employed for data processing in this study. To investigate upper-level draft properties, in-cloud drafts are first identified and filtered using threshold-based criteria. Subsequently, draft statistics and associated thermodynamic and microphysical

properties are analysed. This approach enables a systematic comparison of the properties of upper-level updrafts and downdrafts.

3.1 | The “in-cloud” data

To analyse the dynamical and microphysical characteristics of deep convective clouds, it is essential to classify the data for cloudy points where measurements indicate the presence of clouds. This is achieved using CWC measurements calculated from PSDs. Cirrus and mixed-phase CWC are calculated according to the mass–diameter relationship (as in Krämer *et al.*, 2016), whereas the liquid CWC is calculated directly from PSDs of cloud particles of diameter 3 – $937\ \mu\text{m}$. A non-zero value of CWC indicates a cloudy point. A more detailed explanation can be found in Krämer *et al.* (2020). In the case in which the observed temperature drops below the homogenous freezing level ($235\ \text{K}$), we use the terminology ice water content (IWC) instead of CWC, because all liquid is frozen. This method provides accurate flags for “in-cloud” data, which can later be used for filtering and identifying the cloudy drafts.

3.2 | Defining updraft and downdraft

Updrafts and downdrafts represent ascending and sinking motion in the atmosphere. Positive vertical velocity indicates updrafts, while negative vertical velocity indicates downdrafts. Although various methodologies have been utilised to identify the draft regions in previous studies (e.g., LeMone & Zipser, 1980; Igau *et al.*, 1999; Yang *et al.*, 2016a), fundamentally they all rely on vertical velocity measurements, which indicate directly the movement of the parcel related to dynamical and thermodynamic variations within the cloud layer. In this study, we adopt the approach by LeMone and Zipser (1980), defining drafts as regions where the absolute value of vertical velocity exceeds $0\ \text{m} \cdot \text{s}^{-1}$ continuously for at least 500 m to exclude the effect of small-scale motions. The draft width is calculated from the TAS parameter by aggregating the TAS (distance covered per second) associated with observations based on the duration of a particular draft measurement, in seconds. For all the analysis presented in this study, we use the above method combined with the in-cloud criteria explained in Section 3.1 to identify “cloudy” updrafts and downdrafts.

After filtering, a total of 19,722 s (5.5 h) of data remain, with 16,108 data points from altitudes above 10 km and 3614 data points from below 10 km. Of the drafts identified, 1478 are located above 10 km and 557 are below 10 km.

3.3 | Classification of measurements based on temperature difference

In deep convective clouds, brightness temperature is a good approximation for cloud-top temperature (Machado & Rossow, 1993; Smith & Platt, 1978). It is a common approach to use IR brightness temperature to match the analysis temperature to find the cloud-top altitude (e.g., Minnis *et al.*, 2008). The cloud-top temperature can be compared with the in situ aircraft temperature, which, in the case of an optically thick cloud, will be warmer below the cloud top, thus resulting in a negative temperature difference between brightness temperature (T_b) and in situ temperature ($T_{in situ}$). The optically thin region, on the other hand, is semi-transparent to IR radiation. As a result, the brightness temperatures will be more affected by radiation from the Earth's surface and thus will be warmer than the actual temperature.

The co-location of aircraft position with the satellite dataset is performed by finding the pixel in satellite data nearest to the aircraft position at each time step. Since the aircraft has a higher temporal resolution (1 Hz), each satellite time step is assigned to the aircraft time step within a 30-minute window centred on the satellite time step. Since the campaign mainly sampled through stratiform regions of the anvils, a change in T_b is not expected to introduce a large error during the 30-minute window considered here. This provides us with the temperature difference parameter ($T_b - T_{in situ}$) along the flight track, where the aircraft typically maintains an approximately constant altitude. By analysing the temperature difference distribution, we identified three scenarios: (i) negative temperature differences (< -5 K), which correspond to instances when aircraft flew in optically thick regions below the cloud top, (ii) positive temperature differences (> 15 K), which are attributed to measurements in optically thin regions, and (iii) near-zero temperature differences that indicate a transition region between optically thick and thin regions or instances where the aircraft flew very close to an anvil cloud top (between -5 K and 15 K). The third category has a larger uncertainty associated with the co-location of the cloud system, and it can also include regions that are either connected to or severely detrained from the anvil outflow. Thus, we focus primarily on optically thick and thin regions throughout our analyses, but also include these transition regions for completeness. The threshold values for the temperature difference were determined empirically through trial and error to distinguish the three regimes best (refer to Figure S6), and a detailed sensitivity analysis of these thresholds is provided in Supplementary Section S5 (refer to Figures S7 and S8).

For this classification, we only focus on altitudes in range 10–14 km to classify the measurements. This is (1)

because the sample size at lower altitudes is much smaller and (2) to avoid errors due to mixed-phase clouds at these altitudes, the microphysical and radiative complexity of which leads to larger uncertainties when approximating T_b as cloud-top temperature.

4 | RESULTS

4.1 | Draft statistics

In order to get an understanding of the nature of updrafts and downdrafts observed during ACRIDICON-CHUVA, the draft statistics in terms of draft diameter and air-mass flux associated with all the drafts detected from the dataset are analysed in this section. Cloud properties vary due to different factors such as altitude, life stage of the cloud system, etc. However, it is difficult to characterise the life stage from the measurements used in this study.

The altitudewise statistics are presented in Figure 1. The joint probability density function (PDF) in Figure 1a represents the probability density as a function of draft diameter and altitude. The ratio of observed drafts within each 500-m altitude bin to the total number of drafts is shown as the draft fraction in Figure 1b (grey curve). As indicated by the draft fraction, fewer drafts are observed at lower altitudes compared with the upper levels (10–14 km). This is due to the measurement strategy that prioritised upper-level measurements over the stratiform cloud deck. Generally, narrower drafts occur more frequently than wider drafts (Figure 1a). This is true for both updrafts and downdrafts throughout the altitudes. Drafts at altitudes below 6 km mostly have a diameter less than 3000 m, whereas drafts with diameters greater than 4000 m are present only above 8 km and are slightly more frequent above 10 km. This may not be a characteristic vertical variation, since there is a significantly larger number of measurements of drafts at altitudes above 10 km. The vertical variation of mean and percentile values of draft diameter is presented in Figure 1b. The mean value increases slightly at lower altitudes (up to 6 km) and stays fairly constant up to 10 km. Above that, the mean draft width increases and peaks at approximately 11 and 12 km for updrafts and downdrafts, respectively, then decreases with further increases in altitude. Similarly, the 95th percentile increases with altitude. The peak is observed around similar altitudes to those observed in the mean value curve. Both maximum 95th percentile draft diameter and mean diameter values are higher in downdrafts (10,079 m, 2955 m) than their updraft counterparts (8682 m, 2521 m). The 90% confidence interval represented by the error bars in Figure 1b shows lower variability in the mean curve and larger variability in the percentile

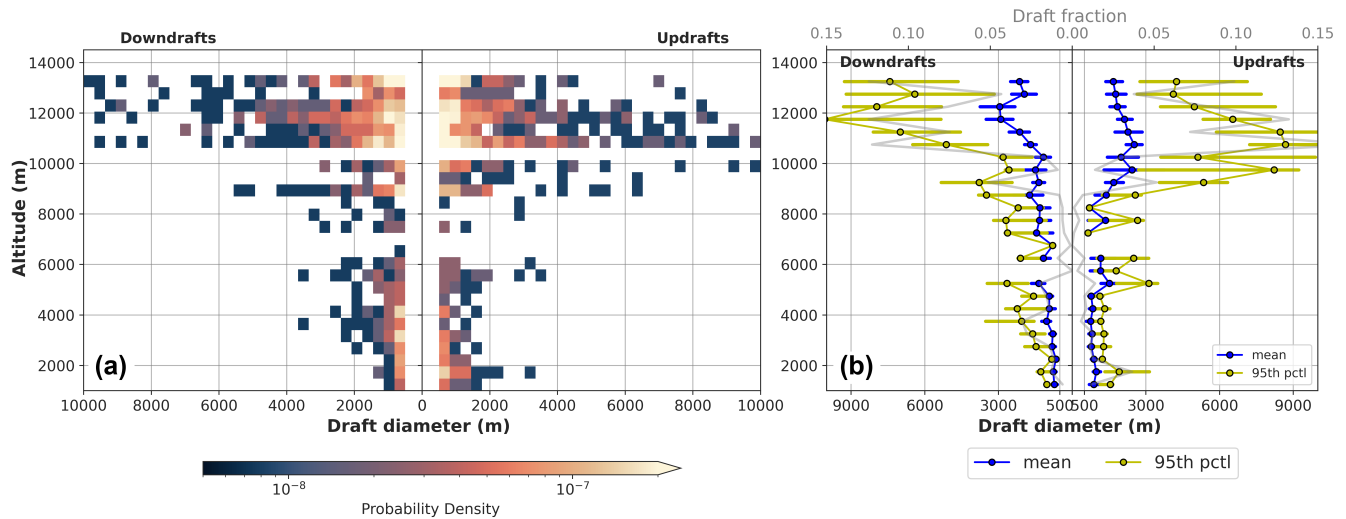


FIGURE 1 Altitudewise draft diameter statistics of all in-cloud drafts. (a) Joint probability density function of draft diameter and altitude. (b) Mean (blue) and 95th percentile (yellow) values of draft diameter and draft fraction (grey), defined by the number of drafts in one altitude bin/total number of drafts. Error bars indicate the 90% confidence intervals for both mean and percentile curves.

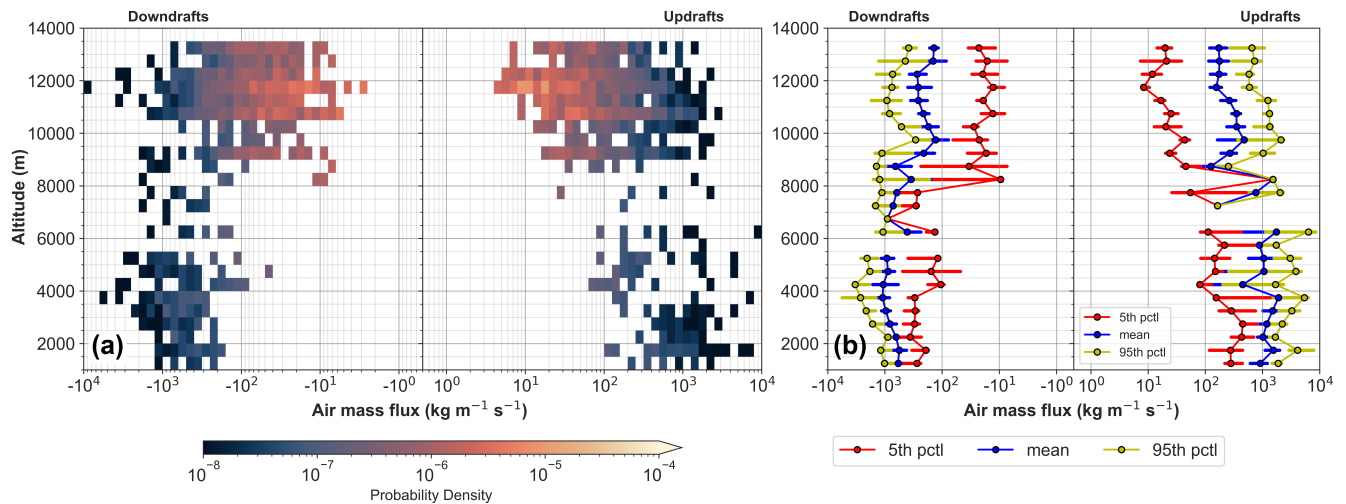


FIGURE 2 Altitudewise air-mass flux statistics of all in-cloud drafts. (a) Joint probability density function of air-mass flux and altitude. (b) Mean (blue), 5th percentile (red), and 95th percentile (yellow) of air-mass flux. Error bars indicate the 90% confidence intervals for both mean and percentile curves.

curve, especially at higher altitudes. This is due to the existence of wider drafts at higher altitudes compared with lower altitudes. The larger draft diameters could be part of mesoscale updrafts and downdrafts in the dissipating anvil clouds, that is, when the cloud top collapses (downdrafts) or in the clouds of a forming anvil (updrafts). The broadening of drafts with altitude, observed in Figure 1, is coherent with previous studies (e.g., Yang *et al.*, 2016a; LeMone & Zipser, 1980), which, however, only extend up to 10 km. The data presented here provide an extension to upper cloud levels (10–14 km), where the drafts are observed to broaden compared with lower altitudes.

The air-mass flux (M) is a measure of the amount of air transported by the draft. This can be calculated using the expression $M = \bar{\rho} \bar{w} D$ (units: $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$), where $\bar{\rho}$ is the mean air density of the draft, $\bar{w}$ is the mean vertical velocity, and D is the draft diameter. The updraft and downdraft air-mass flux statistics are presented in Figure 2. The probability density as a function of air-mass flux and altitude is almost identical for updrafts and downdrafts (Figure 2a) throughout the altitudes. While drafts below 8 km have a minimum absolute air-mass flux of $25 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$ for updrafts and $48 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$ for downdrafts, drafts with weaker absolute air-mass flux values ($< 10 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$)

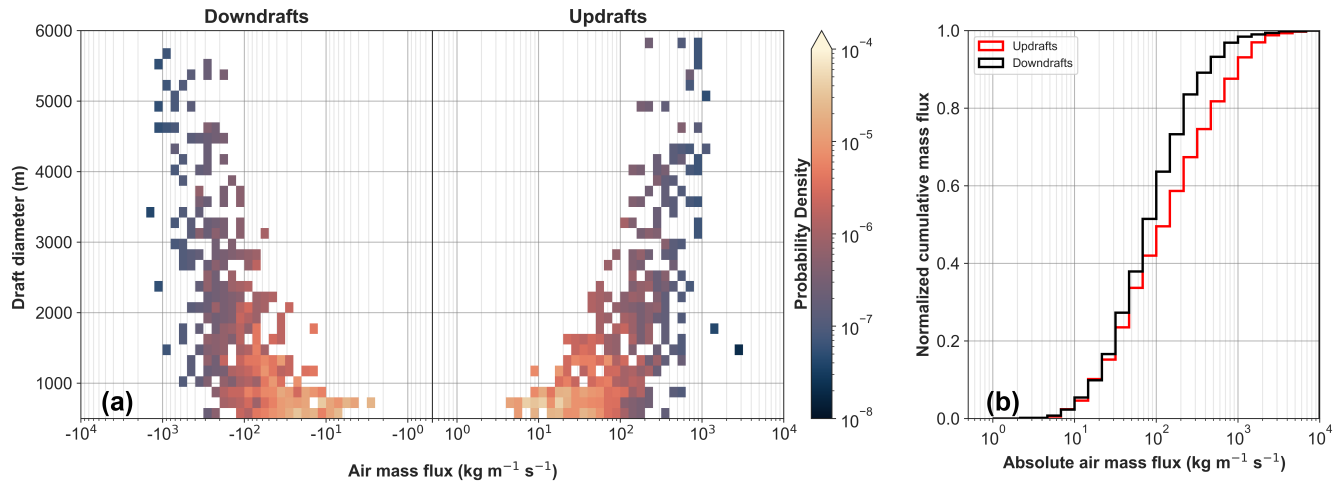


FIGURE 3 (a) Joint probability density function of air-mass flux versus draft diameter. (b) Normalised cumulative mass flux for updrafts (red) and downdrafts (black), with width greater than 500 m at altitudes 10–14 km.

can be seen at altitudes above 8 km. This is due to differences in vertical velocity structure at lower and higher altitudes and the exponentially decreasing air density profile. The majority of the drafts at higher altitudes show very weak mean vertical velocity and low air density. Therefore, despite the fact that they are wider, the overall mass flux values are lower. Drafts at lower altitudes correspond to less width but relatively high mean vertical velocity values and higher air density, resulting in higher air-mass flux. The mean and percentile statistics of air-mass flux are shown in Figure 2b, where both updraft and downdraft air-mass fluxes show a decreasing trend with altitude. The percentile curves follow the mean curves closely, with similar vertical variations. The 90% confidence interval is represented by error bars and shows less spread for the mean air-mass flux curve than for the percentile curves at a given altitude bin. Unlike the draft diameter, the variability does not have a clear trend with altitude. The results in this subsection show that the upper-level drafts are wider and have lower air-mass flux values in anvil clouds compared with the lower-level drafts observed during the campaign. They also provide an overview of the differences in draft characteristics between higher and lower altitudes, considering the fact that previous studies focused mainly on lower altitudes.

Due to the larger number of upper-level measurements, the updrafts and downdrafts observed between 10 and 14 km altitudes alone cover almost 39% and 44%, respectively, of the total updrafts and downdrafts detected, which translates to 28% of the total updraft air-mass flux and 31% of the total downdraft air-mass flux in this campaign. The PDF for upper-level (10–14 km) air-mass flux versus draft diameter of updrafts and downdrafts is given in Figure 3. Consistent with our previous analysis, the updrafts and downdrafts in the upper level show similar

characteristics and are almost mirrored in Figure 3a and in the cumulative absolute air-mass flux curves, which are shown in Figure 3b.

4.2 | Cloud microphysical properties of updrafts and downdrafts: CWC

In this section, we examine the observed characteristics of updrafts and downdrafts in terms of their bulk cloud microphysical properties. Figure 4 shows the statistics of CWC from observations, grouped according to the criteria explained in Section 3.2, for different vertical velocity strengths at different altitude ranges, to view the variations closely. The maximum observed CWC is below 6000 ppmv. The boxplots for altitudes below 5 km show that CWC is similar across different vertical velocity bins, as indicated by the interquartile ranges (IQR), shown as the blue box in the plot. The spread, indicated by the black lines above and below the box, is comparable. However, the median CWCs (specified in the grey boxes) are slightly higher for stronger vertical velocities. At altitudes above 5 km, higher median CWCs are observed in regions of stronger vertical velocities. In general, the probability density distribution of CWC remains similar in both updrafts and downdrafts (cf. Figure S4). Additionally, high and low CWC are present at all altitudes and no particular effect of altitude is observed in CWC characteristics.

To be able to identify the effect of evaporative cooling on downdrafts in the upper levels (10–14 km, thus, rather cooling by sublimation), we classify the data into three regimes based on RH_{ice} : a subsaturated regime ($\text{RH}_{\text{ice}} < 90\%$), a near-saturation regime ($90\% < \text{RH}_{\text{ice}} < 110\%$), and a supersaturated regime ($\text{RH}_{\text{ice}} > 110\%$). The measurements of RH_{ice} could be related to different parts of the

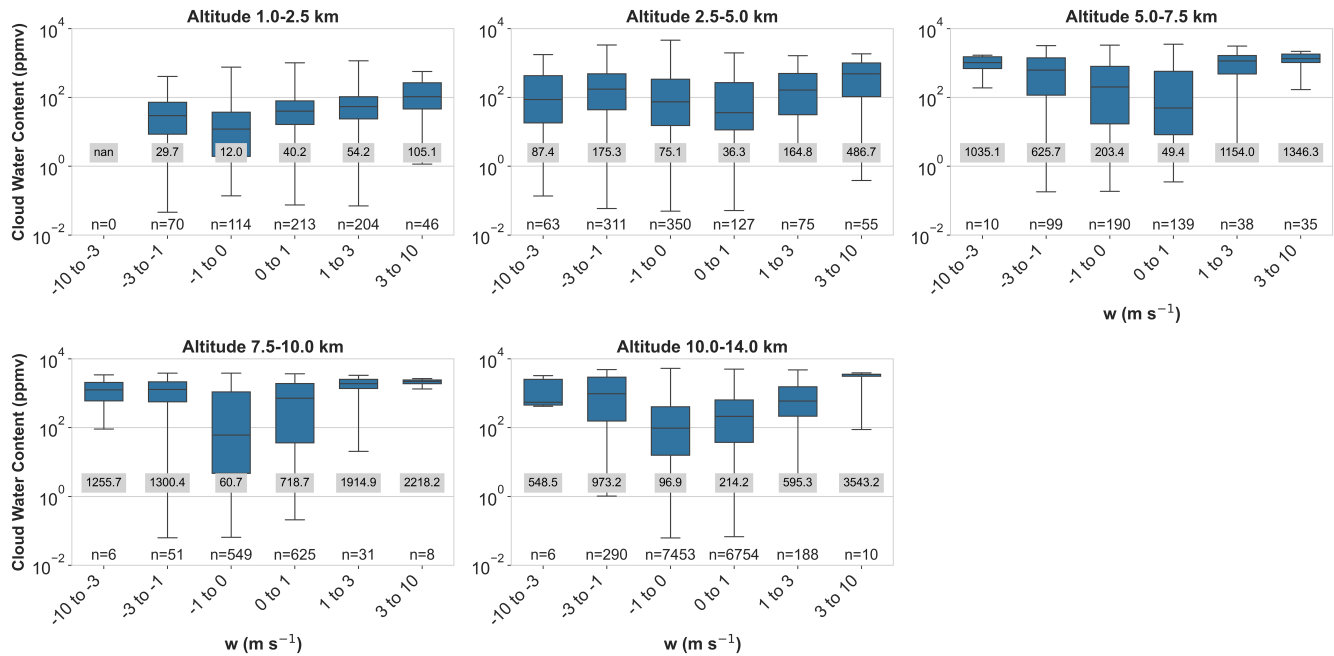


FIGURE 4 Boxplots of cloud water content (CWC, ppmv) in bins of vertical velocity (w , $\text{m} \cdot \text{s}^{-1}$) at different altitude ranges. The horizontal lines inside the boxes are the medians (median magnitudes are annotated in the grey boxes), and the bottom and top sides of the boxes represent the first and third quartiles. The whiskers extend to the minimum and maximum values. n denotes the sample size of each bin.

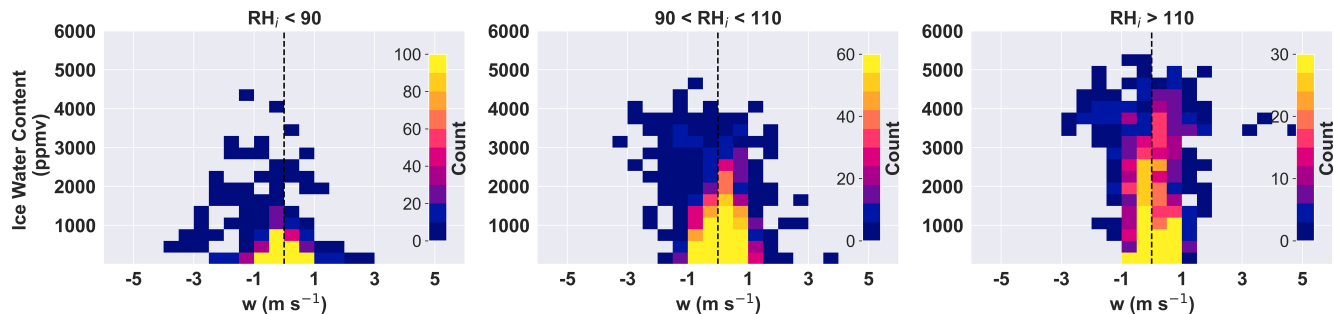


FIGURE 5 Histogram of ice water content (IWC, ppmv) versus vertical velocity (w , $\text{m} \cdot \text{s}^{-1}$) for upper levels (10–14 km) in regimes based on RH_{ice} . (a) Subsaturated ($\text{RH}_{\text{ice}} < 90\%$), (b) near-saturation ($90\% < \text{RH}_{\text{ice}} < 110\%$), and (c) supersaturated ($\text{RH}_{\text{ice}} > 110\%$). In the plots, vertical velocities $w > 0 \text{ m} \cdot \text{s}^{-1}$ correspond to updrafts and $w < 0 \text{ m} \cdot \text{s}^{-1}$ correspond to downdrafts.

cloud (convective core, outflow, cirrus, etc.). For example, supersaturation with respect to ice is very common in cirrus clouds (Comstock *et al.*, 2004). A study based on lidar measurements aboard the HALO aircraft has shown that the RH_{ice} distributions of cirrus clouds vary at different stages of the cloud's lifetime, where RH_{ice} modes are close to saturation in young clouds, supersaturated in mature clouds, and subsaturated in dissipating clouds (Dekoutsidis *et al.*, 2023). Since we are classifying all the available measurements based on RH_{ice} and not focused solely on a particular cloud system, the results presented do not help directly to distinguish the life stages of cloud from RH_{ice} alone.

In the results shown in Figure 5, the subsaturated regime generally contains smaller IWC values, as ice particles sublimate here, whereas the supersaturated regime contains the highest IWC values. The 99th percentile values of IWC in subsaturated and supersaturated regimes are 1586 and 4442 ppmv, respectively. Although a lower IWC is observed in the subsaturated regime, this regime is characterised by comparatively stronger vertical velocities in downdrafts than in the other regimes. In contrast, the highest updraft velocities are found within the supersaturated regime. Notably, we also observe downdrafts in this regime, which we will discuss further in Section 5.

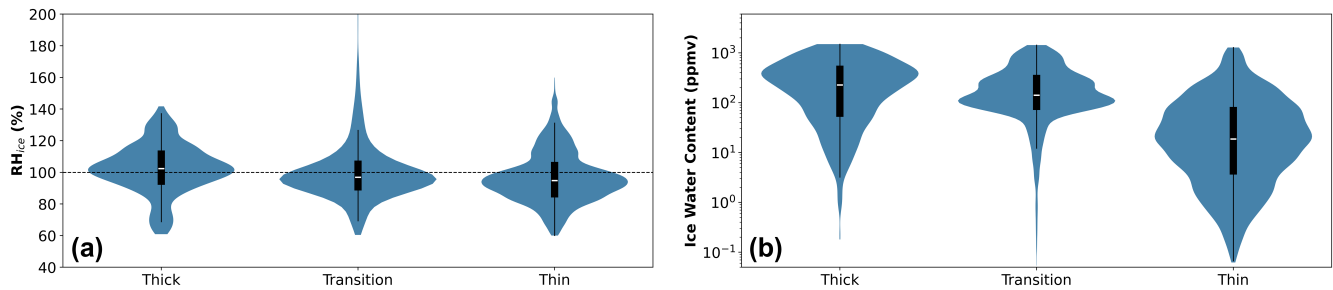


FIGURE 6 Violin plots for (a) RH_{ice} and (b) ice water content at 10–14 km in different cloud regions indicated in the x-axis labels. The violin plots show the statistical distribution. The black boxes extend from the first to the third quartile (interquartile range) and the white line represents the median value. The thin black line extends to values within 1.5 times the interquartile range. We restrict the limit of the violin within the original data range.

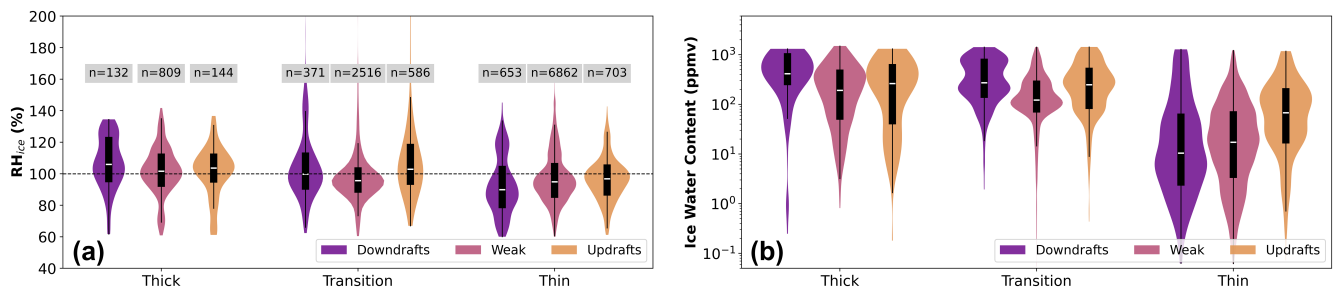


FIGURE 7 Same as Figure 6 but for updrafts ($w > 0.5 \text{ m} \cdot \text{s}^{-1}$, orange shading), downdrafts ($w < -0.5 \text{ m} \cdot \text{s}^{-1}$, purple shading), and weak ($|w| < 0.5 \text{ m} \cdot \text{s}^{-1}$, pink shading). n denotes the sample size that corresponds to each vertical velocity bin for both panels. The construction and meaning of the violin plots are the same as described in the Figure 6 caption.

4.2.1 | Cloud microphysics in regions of different optical thickness

The sensitivity of IWC with respect to RH_{ice} at the upper level is evident from the above analysis. However, it is still difficult to attribute the complex connections of cloud dynamics to cloud microphysical properties by classifying them based solely on sub- or supersaturation. Since saturated environments are common at upper levels (10–14 km), both optically thick and thin regions can attain saturation with respect to ice. Using satellite brightness temperature, we categorise the cloud measurements based on the cloud optical thickness criteria (see Section 3.3).

Figure 6a shows that the median RH_{ice} in optically thick regions (cf. white line on violin plot) is slightly above saturation (103%), whereas in optically thin regions it remains below saturation (94%). The probability of supersaturation is also relatively higher in optically thick regions than in optically thin regions, as indicated by the shape of the distribution in Figure 6a. The IWC from different cloud regions, shown in Figure 6b, exhibits similar variation to RH_{ice} . Not only do the optically thick regions exhibit a median IWC an order of magnitude larger than

the optically thin regions, but they also have a higher probability of large IWC values. The transition region has a median of RH_{ice} and IWC values that lie between those of the optically thick and thin regions.

The classification based on optical thickness is divided further into regions with $|w| > 0.5 \text{ m} \cdot \text{s}^{-1}$, representing updrafts and downdrafts, while measurements associated with $|w| \leq 0.5 \text{ m} \cdot \text{s}^{-1}$ are labelled as “weak”. The results in Figure 7a show that the updrafts and downdrafts in the optically thick and transition regions exhibit higher median RH_{ice} than optically thin regions. Notably, in the optically thick regions, median RH_{ice} in downdrafts is slightly higher (106%) than in updrafts (104%) and downdrafts have a higher probability of being supersaturated. Additionally, the downdrafts across all cloud regions show a bimodal distribution in RH_{ice} , with saturated and supersaturated modes for both optically thick and transition regions and subsaturated and supersaturated modes for optically thin regions. Similarly to RH_{ice} , Figure 7b shows that the median IWC in downdrafts is comparatively higher than in updrafts in the optically thick regions, while in optically thin regions the median IWC is lowest in downdrafts and highest in updrafts. In general, there are more samples from optically thin regions than optically

thick regions, which seems logical when considering that the optical thickness of anvil clouds decreases with distance from the convective core (Sokol & Hartmann, 2020).

The analysis presented in this section highlights the variations of IWC and RH_{ice} in different cloud regions. Although the effect of vertical motion does not control IWC directly, it exhibits distinct behaviour in regions with strong and weak vertical motion and depends on the cloud region sampled.

4.3 | Particle size distributions in updrafts and downdrafts

To gain an understanding of how PSDs vary with altitude and vertical velocity, we use the PSDs from NIXE-CAPS, where the size distributions have been categorised into altitude bins 1.0–2.5, 2.5–5.0, 5.0–7.5, 7.5–10.0, and 10.0–14.0 km. The PSDs in each altitude bin are split further according to absolute values of vertical velocity: 0–1 $m \cdot s^{-1}$, 1–3 $m \cdot s^{-1}$, and the last bin contains all the observations having an absolute vertical velocity greater than 3 $m \cdot s^{-1}$. This is done separately for updrafts and downdrafts. The mean PSDs for each category are shown in Figure 8, which exhibits changes with respect to the altitude and intensity of vertical velocity. The melting level (273.15 K) is located around 4.5 km during the campaign. From the observed temperature range (as indicated in the figure panels), it can be deduced that clouds at altitudes above the melting level, up to 10 km, are in the mixed-phase regime (Cecchini *et al.*, 2017b; Jäkel *et al.*, 2017) with temperatures between 273.15 and 235 K. The temperatures in the uppermost altitude bin (10–14 km) are below the homogenous freezing level (235 K). One can note that the strongest updrafts and downdrafts ($|w| > 3 m \cdot s^{-1}$) show the largest number concentrations of particles with sizes $D_p < 100 \mu m$ at altitudes above 5 km. The separation between mean PSDs for particles $D_p < 100 \mu m$ for different vertical velocities increases from lower to higher altitudes up to the 7.5–10 km range. In the upper levels, this separation is relatively smaller. Figure 8 also shows increasing number concentrations of larger particles ($D_p > 100 \mu m$) with altitude, consistent with Yang *et al.* (2016b), and we can see this increasing trend extending from the mixed-phase regime (which has been the focus of other studies) to beyond the homogenous freezing level.

Number concentrations of larger particles ($D_p > 100 \mu m$) increase more noticeably from lower to higher altitudes in stronger drafts. Updrafts carry particles from below, where they are subject to different growth processes according to the thermodynamic conditions. For example, Yang *et al.* (2016b) observed by analysing PSDs in

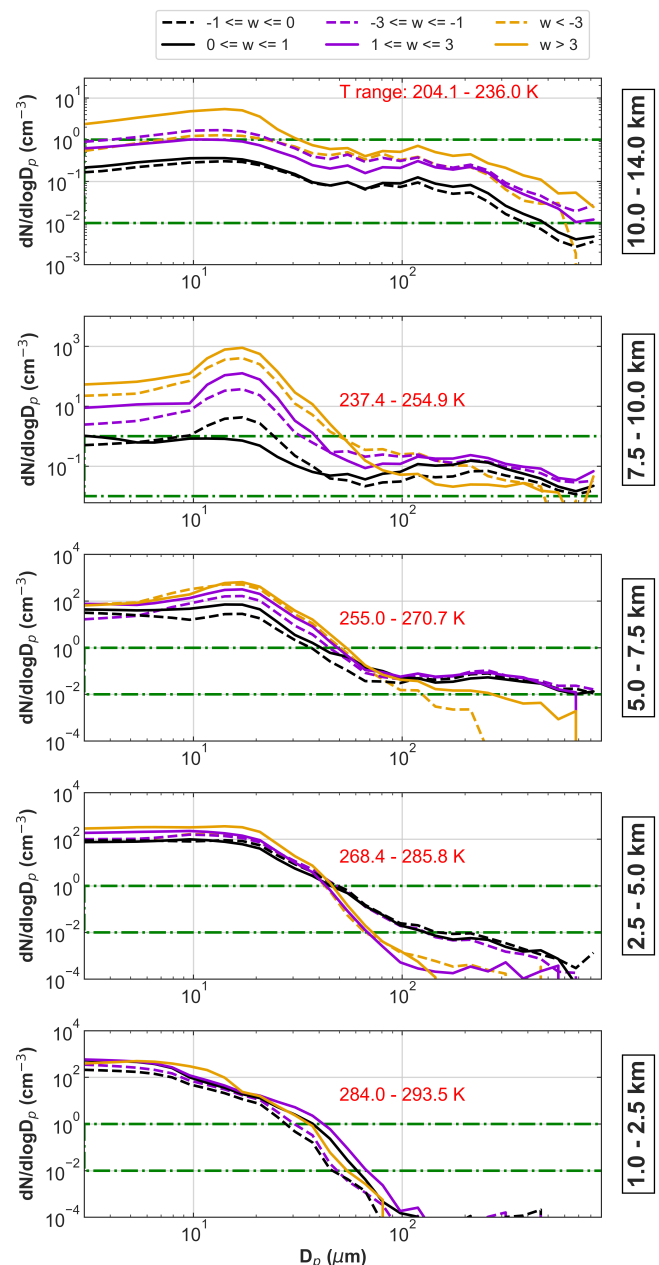


FIGURE 8 Mean particle size distributions for in-cloud updrafts and downdrafts at different altitudes. Solid lines denote updrafts, dashed lines denote downdrafts, and colours indicate vertical velocity bins. Green dash-dotted reference lines denote concentrations of 10^{-2} and $1 cm^{-3}$ to guide the reader.

mixed-phase clouds that there are more millimetre-sized particles in stronger updrafts at the cloud top, and they attributed it to larger ice particles generated in stronger updrafts. These particles can also simply be carried aloft by the updrafts. It is unclear what causes the presence of larger particles in downdrafts and their increasing number concentrations with altitude and draft intensity. The downdraft size distributions (dashed lines) are very similar

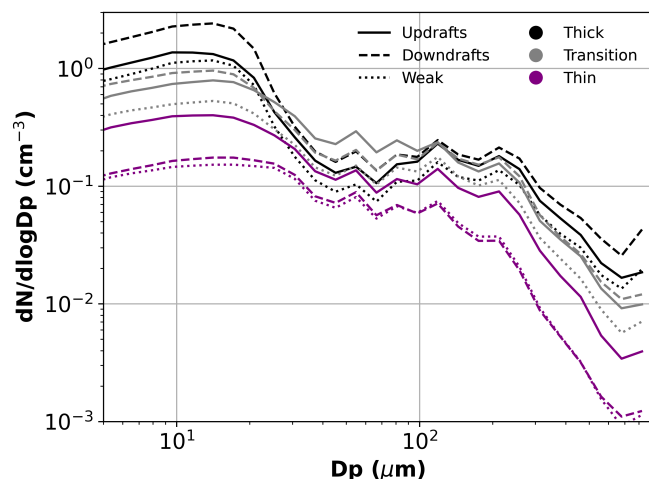


FIGURE 9 Mean particle size distributions between 10 and 14 km for optically thick (black curves), transition (grey curves), and optically thin (purple curves) cloud regions. Solid, dashed, and dotted lines correspond to updrafts ($w > 0.5 \text{ m} \cdot \text{s}^{-1}$), downdrafts ($w < -0.5 \text{ m} \cdot \text{s}^{-1}$), and weak vertical motion ($|w| < 0.5 \text{ m} \cdot \text{s}^{-1}$), respectively.

to the updraft size distributions (solid lines) with similar absolute vertical velocities, except for the 5–7.5 km range. In this (5–7.5 km) altitude range, the mean size distribution for strong downdrafts ($w < -3 \text{ m} \cdot \text{s}^{-1}$) shows lower number concentrations for particles with $D_p > 100 \mu\text{m}$ and smaller maximum sizes than the updrafts. This could be related to fewer measurements in this altitude range, making the results less representative, especially for stronger drafts.

4.3.1 | Changes in PSDs within regions of different optical thickness

In addition to vertical motion influencing PSDs, the location within the cloud can also play a significant role, as it affects the availability of water content directly (see Section 4.2.1). To understand these effects, the PSDs in the 10–14 km altitude range, across different cloud regions, are analysed in Figure 9. While the shape of PSDs remains relatively consistent across all cloud regions, optically thick regions (black curves) exhibit higher particle number concentrations across all size ranges compared with optically thin regions (purple curves). This difference in particle concentrations is particularly pronounced for small particles ($D_p < 30 \mu\text{m}$) and large particles ($D_p > 100 \mu\text{m}$).

Furthermore, in the optically thick regions, the downdraft PSD exhibits the highest particle number concentrations over all sizes. The particle number concentrations in the updrafts resemble those of regions with weak vertical motion. For optically thin regions, the highest particle

number concentrations are found in the updrafts, especially for large particles ($D_p > 100 \mu\text{m}$). Due to severe icing, vertical velocity measurements were unavailable for parts of the optically thick cloud sampling period, which has reduced the average particle number concentration, particularly in the size range 30–100 μm in the optically thick regions (see Figure S9 in the supplement for more detail).

5 | DISCUSSION

5.1 | Anvil draft statistics and comparison with previous studies

From analysing the observed vertical velocities, we find that the vertical velocity is relatively weaker (by roughly $2 \text{ m} \cdot \text{s}^{-1}$) in this campaign, compared with previous studies (LeMone & Zipser, 1980; Yang *et al.*, 2016a), which focused on the convective core of the clouds, whereas the measurements presented in this study are from anvil clouds. However, the observed air-mass fluxes are of the same order of magnitude. This could be due to the fact that the observed drafts are slightly wider and compensate for the weaker vertical velocities. The relationship between mean air-mass flux and draft diameter, shown in Figure 3 for upper-level drafts, is found to have a similar relationship to that of the lower-level drafts analysed in previous studies (e.g., Yang *et al.*, 2016a), with draft diameter increasing with air-mass flux. The in-cloud mass fluxes presented in this study are only representative of convective-scale motions and may differ from mass fluxes at different scales, such as those of a global climate model (GCM) grid.

While we have defined drafts to have a width of at least 500 m (Section 3.2), other studies used lower thresholds (e.g., Yang *et al.*, 2016a). In order to test the sensitivity of the chosen draft width threshold, we repeated our analysis by including drafts between 100 and 500 m (Figures S1–S3). Due to the high aircraft speed of HALO, single-point observations will be mostly classified as drafts larger than 100 m. Drafts with diameters of 100–500 m contribute to more than 70% of the total up- and downdrafts detected, with almost 30% contribution to updraft and downdraft air-mass fluxes. Thus, the main contribution to up- and downdraft mass fluxes stems from the wider drafts as characterised in our study (width $> 500 \text{ m}$). The mean profiles show smaller values for diameter and air-mass flux (Figures S1b and S2b) with the inclusion of narrow drafts. The 95th and 5th percentiles decrease due to the presence of a higher number of small diameters and lower air-mass fluxes in the distribution. Nevertheless, the mean draft diameter broadens (Figure S1b) from

lower to upper levels. The inclusion of narrower drafts increased the frequency of weaker air-mass flux values at all altitudes (Figure S2). Thus, the air-mass fluxes show almost equal strengths in both the upper and lower levels. This result is similar to that of Yang *et al.* (2016a), who found no obvious trend between air-mass flux and altitude in their respective altitude range (which includes temperatures within -15°C). In contrast to the lower altitude air-mass flux-draft diameter relationship shown in Yang *et al.* (2016a), this relationship shows similar characteristics for updrafts and downdrafts in the upper levels in our study (Figure S3). We would like to emphasise that our study does not include the core of the convective system, due to the aircraft limitations in probing regions with strong vertical motions, where vertical velocity magnitudes are strongest during the dry season (Giangrande *et al.*, 2023; Machado *et al.*, 2018).

5.2 | Microphysical influence on draft dynamics

Vertical motion, as mentioned in Knupp and Cotton (1985), is strongly affected by the amount of hydrometeors present in the air. In this context, CWC has been analysed as a proxy for the mass of hydrometeors in order to assess its influence on the observed vertical velocity in updraft and downdraft regions. Grant *et al.* (2022) demonstrated this further by highlighting a robust linear relationship between the updraft vertical velocity and the accumulated rate of condensed water from a range of cloud-resolving model simulations of tropical and mid-latitude deep convective cloud systems with horizontal resolutions between 250 and 300 m. They show that the net effects of all microphysical processes, such as condensation, evaporation, deposition, sublimation, and cloud droplet activation, vary linearly with updraft velocity. However, the aircraft data used in this study do not provide the rate of condensate converted from water vapour, as information on the timely evolution (history) of the variables measured is not available. From our analysis, the observed median CWC increases with vertical velocity for updrafts (Figure 4).

Weight-induced drag by hydrometeors can lead to downdrafts and is considered one of the main drivers for precipitation-driven downdrafts, according to Houze Jr (2014, p. 190). Thus, higher CWC values should correspond to stronger downdrafts due to the higher drag force. Although with high spread, the median CWCs are higher in stronger downdrafts than in weaker downdrafts (Figure 4), but less pronounced at the lower altitudes where the precipitation-driven downdrafts are located, and no complicated ice microphysics might interfere with

the drag effect. Another scenario to consider in determining the amount of CWC is adiabatic compression and warming in downdrafts. This lowers the relative humidity of the downdraft parcel and, once subsaturated, reduces CWC through evaporation or sublimation. Furthermore, stronger downdrafts may reduce CWC faster due to increased adiabatic compression and consequent warming. This potential inverse relationship between downdraft strength and CWC is also not observed in our analysis. Instead, the median CWC increases with the strength of the vertical velocity irrespective of its sign.

In Figure 5, we observe strong downdrafts in the supersaturated regime where sublimation is not possible due to supersaturation. By analysing measurements based on the brightness temperature, we can see that this supersaturation in downdrafts is more common in optically thick regions (Figure 6a). The optically thick regions have both the highest median RH_{ice} and IWC, in contrast to optically thin regions, where both median RH_{ice} and IWC are the lowest in updrafts and downdrafts. This aligns with the cirrus cloud RH_{ice} and IWC relationship, as in Krämer *et al.* (2020), where RH_{ice} and IWC increase/decrease together. Furthermore, we observe that the downdrafts in optically thick regions exhibit a slightly higher median RH_{ice} and a higher median IWC than the updrafts (Figure 7a). Moreover, bimodality in the RH_{ice} distributions of downdrafts indicates that they are more likely to be supersaturated. This does not align with the generally accepted view of downdrafts being subsaturated and thus evaporatively driven (e.g., Knupp & Cotton, 1985; Pawlowska-Mankiewicz, 1987).

The observations showing the supersaturated regime in Figure 5 originate from several downdrafts from different flights. Although there are studies using numerical models that have pointed out the existence of supersaturation in downdrafts in ice clouds (D'Alessandro *et al.*, 2017), a comprehensive explanation is lacking. A possible explanation relates to the existence of older updraft cores, which are often followed by a convective-scale downdraft at mid to upper levels (Houze *et al.*, 1989) of a deep convective system. Here, the maintenance of these downdrafts may be governed by the inertia from older updraft cells rather than latent cooling processes. Thus, the presence of downdrafts in the supersaturated regime is an interesting feature to explore further with numerical simulations, as they also provide the potential to focus on the evolution of drafts.

The observed PSDs in the upper levels (Figure 8) show that the mean PSDs in updrafts and downdrafts are largely similar, exhibiting only minor differences. The increasing trend in cloud particle number concentration with downdraft intensity suggests processes that produce more particles. For instance, ice multiplication processes have a significant impact on number concentrations in numerical

weather prediction (NWP) model simulations and idealised large eddy simulations (LES: Han *et al.*, 2024). Although their dynamical link is still not understood, it is certainly conceivable that, in more intense drafts, more turbulence might provide the possibility of ice particles colliding, which increases the chances for breakup or splintering processes, thereby leading to larger ice particle number concentrations. It seems conceivable that differences in fall speeds of cloud particles in updrafts and downdrafts would have an influence on the size distributions. Although it is not possible to assess this influence with the dataset analysed, previous studies that looked into the terminal fall velocity of ice crystals in still air found that the terminal fall velocity depends largely on crystal shape (cf. fig. 10-42, Pruppacher & Klett, 2010), and for particles smaller than 1 mm it is generally (far) below $0.6 \text{ m} \cdot \text{s}^{-1}$. For the observations presented here, this implies that particle fall velocities are smaller in magnitude than the draft velocities in stronger drafts ($|w| > 1 \text{ m} \cdot \text{s}^{-1}$). Thus, they get transported with the draft, and we would not expect a significant influence of the fall speed on the size distributions. In weaker drafts, one might expect an effect of fall velocities at least for larger particles. However, as shown in Figure 8, the shapes of the size distributions remain very similar for all up/downdraft strengths, indicating that fall velocities do not play a major role.

Given the lack of directly comparable data that outline the effect of vertical velocity on mean PSDs, it is difficult to evaluate these results comprehensively with other studies. To enable an indirect analysis, we assume that, if we have measurements of a growing system, it contains stronger drafts. Thus, our strong drafts could be compared with young deep convective clouds, such as in Frey *et al.* (2011, see their fig. 19, also provided in the supplement). This could imply that the mean PSDs from young outflow regions can be compared with upper-level mean PSDs in the stronger vertical velocity bin, shown in Figure 8. PSDs show a similar structure for both the upper-level PSDs shown in this study and the PSD of the young outflow of a MCS shown in Frey *et al.* (2011). Additionally, identical to upper-level PSDs, young outflow clouds are observed to have the highest number concentration and the largest maximum particle size.

The higher particle number concentrations in the upper levels are also related to the availability of water content. For example, for optically thick regions (Figure 6b), the mean PSD (black curve, Figure S9b) has higher number concentrations than in optically thin regions. Although other cirrus studies (e.g., Krämer *et al.*, 2025b) have attributed increasing updrafts to high IWC, here, we observe relatively high IWC in both updrafts and downdrafts in optically thick regions, and low IWC occurs at regions of weak vertical motion. The downdrafts detected

in this dataset show very high particle number concentrations (especially at $D_p < 30 \text{ } \mu\text{m}$) in optically thick regions, along with high RH_{ice} , indicating the possibility of ice nucleation in downdrafts as well. The high number concentrations of larger particles in downdrafts indicate either growth in supersaturated downdrafts or mixing between updrafts and downdrafts.

From previous studies, it is unclear what difference can be expected in particle size distributions of upper-level updrafts and downdrafts. Heymsfield *et al.* (2009) have found that updrafts carry larger particles from lower altitudes or smaller particles, including recently nucleated primary ice, frozen droplets, and rimed particles. Upper-level downdrafts, based on their origin, may carry only smaller particles, as there are no larger particles naturally available at upper levels. However, the updrafts and downdrafts show some striking similarity in their properties, for instance, in their particle size distributions as shown in Figure 8. A possible explanation could be the existence of eddies that allow mixing between the drafts. From analysing the average PSDs in updrafts and downdrafts located next to each other, and the area outside the draft structure from two flight segments (refer to Figure S5), it is observed that the PSDs of updraft/downdraft couples are comparable, but are different from the PSDs of the regions outside the draft structure, which exhibit lower number concentrations of cloud particles. Due to the high aircraft speed ($150 \text{ m} \cdot \text{s}^{-1}$) resulting in shorter time spent in the smaller drafts, it is not possible to calculate the actual eddy scales, which would play a role here, using methods like auto-correlation, as a larger amount of data is required inside the drafts for such analysis.

6 | CONCLUSIONS

The anvil cloud draft characteristics in deep convective clouds are studied using aircraft measurements from the ACRIDICON-CHUVA campaign over Amazonia, Brazil, during the transition from the dry to the wet season. To examine the draft characteristics systematically, we filtered the measurements to include only in-cloud drafts with a width of at least 500 m to analyse the width and air-mass flux statistics of the drafts. Furthermore, the difference between satellite brightness temperature and in situ aircraft temperature is used to classify the measurements into optically thick and optically thin regions. The influence of cloud dynamics on thermodynamic and microphysical characteristics is studied by analysing the RH_{ice} , IWC, and average particle size distributions.

Upper-level drafts (10–14 km) are wider and exhibit lower air-mass fluxes than drafts at lower levels due to

weaker vertical velocities and lower air density. IWC is similar in both updrafts and downdrafts, and shows no obvious tendency with vertical velocity. Large negative vertical velocities ($w < -2 \text{ m} \cdot \text{s}^{-1}$) are observed even in the supersaturated regime, which challenges the conventional understanding that downdrafts are driven primarily by evaporative or sublimational cooling. A more detailed analysis by classifying the measurements into optically thick and optically thin regions reveals that clouds in the former regions show higher median RH_{ice} and IWC. The downdrafts in optically thick regions are equally supersaturated to the updrafts and contain higher IWC than updrafts. We speculate that these upper-level downdrafts may be driven by inertia from older convective cells that are located at progressively higher altitudes as their distance from the convective core increases (Houze *et al.*, 1989). However, the relative importance of dynamical and thermodynamical factors in driving and maintaining these downdrafts and drafts in general cannot be determined with the dataset used in the current study. This will be explored using high-resolution large eddy simulations in a follow-up study.

The mean particle size distributions show an increase in maximum particle size with altitude, consistent with previous studies. Notably, the strongest draft regions show higher concentrations of particles $D_p < 100 \mu\text{m}$ and a faster increase in number concentrations of large particles ($D_p > 100 \mu\text{m}$). Updraft and downdraft PSDs have similar shapes within the same altitude range, but the magnitudes of number concentrations vary between them. Unsurprisingly, PSDs from optically thick regions show higher particle number concentrations than those from optically thin regions. Within these optically thick regions, the particle number concentrations are observed to be higher in downdrafts than in updrafts. The higher number concentrations in downdrafts could be a result of multiple processes, including nucleation or ice multiplication processes.

Analysing in situ measurements, we were able to point out the effects of interactions between vertical motion and microphysics, for instance, increasing cloud particle number concentration in stronger vertical velocity regions. However, these relationships cannot be expressed as simple correlations. Notably, our findings reveal that the downdrafts in optically thick regions contain higher supersaturations than updrafts. We also found that these downdrafts exhibit higher IWC and particle number concentrations. These results indicate that processes other than those in water clouds might drive and maintain downdrafts in ice clouds, pointing out the need for further research to understand how downdrafts are driven/maintained (in upper, but also lower levels), utilising more observations and numerical modelling.

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DATA AVAILABILITY STATEMENT

The data are available through mission-based databases. They can be accessed after signing a data agreement. The permanent URL for ACRIDICON-CHUVA via the DLR HALO database is <https://halo-db.pa.op.dlr.de/list/missions> (last accessed February 3, 2026). Cloud microphysics data have been retrieved from Krämer *et al.* (2025b). NCEP/CPC GPM_MERGIR data are available from NASA GESDISC (Janowiak *et al.*, 2017).

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