

Dear Referee #1 and Referee #2,

We sincerely thank you for the careful, detailed, and constructive reviews of our manuscript. We greatly appreciate the time and effort dedicated to evaluating our work and providing insightful comments and suggestions. The reviewers' feedback has significantly improved the clarity, structure, scientific rigor, and overall quality of the manuscript.

In the present compiled response document, the authors' initial replies to the referees' comments, as published online during the discussion phase, are shown in **blue**, while the modifications incorporated into the revised manuscript are indicated in **red** in the final compiled version.

Following the reviewers' recommendations, the manuscript underwent a major revision, including substantial reorganization of several sections, clarification of the theoretical framework, expansion of the uncertainty and sensitivity analyses, improvement of the discussion of the thermodynamic assumptions, and revision of figures, captions, and supplementary material. Additional analyses and explanations were also included to address all concerns raised by the referees.

A new repository folder was created to provide the updated processed aircraft data and codes described in the manuscript, which are available at: <https://doi.org/10.5281/zenodo.20278305>.

We believe that these revisions have substantially strengthened the manuscript and adequately addressed the reviewers' comments and concerns. Therefore, we respectfully submit the revised version for further consideration and hope that the manuscript is now suitable for final publication in Atmospheric Chemistry and Physics.

We again thank the referees for their valuable contributions to improving this work.

Sincerely,

Ramon Braga, Manfred Wendish, Rachel Albrecht and Daniel Harrison

Response referee #1

Title: Energetically Stringent Quantification of Water Vapor Supersaturation at Cloud Base

Authors: Braga et al.

Recommendation: Rejection

Overall comments:

This manuscript proposes a new thermodynamic framework to infer cloud-base water vapor supersaturation (S_v) by treating the ascent of a saturated air parcel as a reversible cloud-adiabatic process with conserved isobaric enthalpy, and then partitioning the latent heating term (Q) into internal-energy (ΔU) and saturation-work (W_s) contributions. The authors then compare inferred $N_d(S_v)$ spectra at Amazonian cloud bases with below-cloud $CCN(S_v)$ spectra and report agreement within stated uncertainty bounds.

The manuscript is novel and potentially interesting, especially in its attempt to connect cloud-base supersaturation to an explicit energetic closure using aircraft observations. The observational dataset is also valuable. However, I am afraid that the thermodynamic interpretation is not yet sufficiently demonstrated or justified for publication. The conceptual novelty is promising, but the derivation, physical interpretation, sensitivity analysis, and validation strategy all need substantial strengthening before the main claims can be accepted. The manuscript also contains a potential overstatement in its conclusions about standard adiabatic models "overestimating" liquid water content, latent heating, buoyancy, and updraft speeds. Furthermore, the structure of the manuscript also needs substantial revision. Finally, this manuscript appears to be poorly written with many instances of unnecessary repetition.

Therefore, I do not think the manuscript is publishable in its current form. I hope my comments will be received as constructive and helpful to the authors. Considering the time and effort the authors might need to address the following concerns and comments, I recommend rejection of the manuscript.

Major comments:

1. Equation derivation and the decomposition of Q and S_c .

Even though the authors spent a lot of effort showing the equation derivations, I am afraid that it is still very difficult and not logical enough for readers to follow. My main concern is that the manuscript appears to jump too quickly from an energy-budget $Q = \Delta U + W_s$ to a new definition or decomposition of supersaturation $S_c = S_l + S_v$, where S_l and S_v are assigned in proportion to $\frac{\Delta U}{Q}$ and $\frac{W_s}{Q}$. The manuscript states this explicitly in

Section 2.3 with equations 22-24. But supersaturation is a thermodynamic disequilibrium state variable defined by vapor pressure or saturation ratio, while ΔU and W_s are path-dependent energetic terms. I think the paper needs a much clearer and firmer derivation showing why this partition is plausible and unique. At present, it reads more like a proposed energetic analogy. The paper needs to prove that this decomposition really follows the first law of thermodynamics and the Clausius-Clapeyron relation, and is not simply a convenient remapping. Therefore, the authors should either provide a firmer and cleaner derivation or

explicitly reframe the method as a physically motivated diagnostic framework.

A: We thank the reviewer for this important comment. We agree that the relationship between the energy budget and the supersaturation partition can be presented more clearly and in a more structured manner. Below, you find a significantly improved introduction of the proposed method and a firm clarification of the relationship between the energy budget and the Clausius-Clapeyron relation.

In the current manuscript, we describe the ascent of a saturated parcel assuming the following thermodynamic conditions:

- Adiabatic parcel: no heat is exchanged with the surroundings ($\delta Q_{\text{ext}} = 0$);
- The energy budget is calculated for isobaric conditions: the small variability in pressure at the cloud base during the ascent (~ 0.1 - 0.3%) is negligible.
- For isobaric conditions, the total heat (latent heat) in the parcel results from phase change (vapor to liquid). During condensation, the latent heat released is the enthalpy difference ($Q = dH$). See section 1 below for description.
- The energy (or latent heat) budget of the parcel is calculated using the first law of thermodynamics; the change in enthalpy for isobaric conditions is given by $Q = dH = dU + W_s$. Since the air parcel is isobaric and saturated, the energy budget depends only on pressure and temperature, and thus dU and W_s are process-dependent. Sections 2 and 3 describe the proposed energy budget and the invertibility of the energetic parameters, respectively. The partition of the cloud supersaturation is described in section 4.

Important information: The “reference-state of saturation ratio”- RHc described in the submitted manuscript was long and confusing. We decided to calculate RHc based on the classical Bolton equation for es(T), as shown below. This is more accurate and leads to minor relative differences in the absolute values of Sc, Sl, and Sv shown in the submitted version. Furthermore, it clarifies the relationship between the energy budget proposed and the Clausius-Clapeyron relation.

Below are some clarifications of the method. Some of the symbols are not available in the submitted manuscript and will be added further. Furthermore, the references mentioned here are available in the submitted version.

1) Calculation of the latent heat and cloud supersaturation

The energy (latent heat) of the saturated parcel is limited by the enthalpy difference of the phase change from vapor to liquid, $Q = dH$, and can be written in finite forms as follows:

$$Q = \Delta H \quad \therefore \quad L_v \cdot q_l = -c_{p,\text{cloud}} \cdot \Delta T = -c_{p,\text{cloud}} \cdot (T_0 - T) \quad (1)$$

During the phase change, the internal energy decreases ($T_0 > T$) as q_l (liquid water mixing ratio) and the latent heat of condensation (Q) increase. We assume the warmer temperature (T_0) in the $c_{p,\text{cloud}}$ (i.e., $c_{p,\text{cloud}} = c_{pd} + c_{pv} r_s(T_0) + c_{pl} q_l$) and L_v calculations, as it represents the initial condition of the saturated parcel. For small temperature differences ($< \sim 1$ K), the specific heat

capacity of the cloudy air ($c_{p,cloud}$) varies only weakly with r_s (saturated mixing ratio) and q_l .

The phase change process leads to an increase in the air temperature, in this case the equivalent temperature (T_e), and is constant during the ascent (shown in the figure above), i.e.:

$$T_e = T + \Delta T_Q = T_0 = T_{air} \quad (2)$$

Where,

$$\Delta T_Q = \frac{L_v \cdot q_l}{c_{p,cloud}} \quad (3)$$

1.1 RHc (reference-state saturation ratio)

The formulation of relative humidity - RH describes the amount of water vapor in the air relative to the amount of water vapor in the air when it is saturated for a given temperature, i.e., the saturation ratio, and is defined as follows:

$$RH = \frac{e(T)}{e_s(T)} \quad (4)$$

Where $e(T)$ is the water vapor pressure (Pa), $e_s(T)$ is the saturation water vapor pressure (Pa), and T is the air temperature (K or °C) (Bolton, 1980; Rogers and YAU, 1989).

The values of $e_s(T)$ can be calculated for a wide range of temperatures ($-30\text{ °C} \leq T_c \leq 35\text{ °C}$) with minor uncertainties ($\sim 0.1\%$) as follows (Bolton, 1980):

$$e_s = 611.2 \cdot \exp\left(\frac{17.67 \cdot T_c}{T_c + 243.5}\right) \quad (5)$$

For a saturated parcel under isobaric conditions, T_c is the dew point temperature (T_d) in °C.

The reference-state saturation ratio of a saturated parcel or cloud (RHc) undergoing expansion (cooling) is calculated as follows:

$$RH_c = \frac{e_s(T)}{e_s(T_0)} \quad (6)$$

The cloud supersaturation (S_c) is formulated as follows:

$$S_c = RH_s - RH_c = 100 - RH_c \quad [\%] \quad (7)$$

where $RH_s = 100\%$ is the saturation ratio at the reference state (T_0), and S_c expresses the thermodynamic excess of water vapor relative to equilibrium with respect to liquid water at the reference state. Since the cooling process is related to the increase of q_l (shown in Eq. 1), the increase in S_c is associated with vapor-liquid conversion and Q .

2) Calculation of energy budget using the first law of thermodynamics

According to the first law of thermodynamics, the change in internal energy of a closed system is determined by the balance between heat exchange and pressure-volume work. For an isobaric process involving only pressure-volume work, the change in enthalpy (dH) can be interpreted as the sum of the change in internal energy and the expansion work performed by the system. Under adiabatic conditions, the dH equals the heat exchanged at constant pressure by a saturated parcel. Thus, for a saturated parcel undergoing condensational growth from the reference state, the latent heat released ($Q=dH$) is the source of heat in the thermodynamic system, and the energy budget can be calculated following the first law as follows:

$$Q = \Delta U + W_s \quad (8)$$

where Q represents the latent heat released by condensation, ΔU is the change in internal energy of the parcel associated with vapor-liquid conversion, and W_s is the work associated with the expansion of water vapor.

Analogous to eq. 1 above, the energy budget from eq. 8 can be calculated as follows:

$$L_v \cdot q_l = -c_{p,cloud} \cdot \Delta T_{ws} + r_{s0} \cdot R_v \cdot T_0 \cdot \ln\left(\frac{\alpha_{vs}}{\alpha_{v0s}}\right) \quad (9)$$

Or

$$L_v \cdot q_l - r_{s0} \cdot R_v \cdot T_0 \cdot \ln\left(\frac{\alpha_{vs}}{\alpha_{v0s}}\right) = -c_{p,cloud} \cdot (T_0 - T_{ws}) \quad (10)$$

Note that the W_s term assumes the parameters of the initial conditions of the saturated parcel (T_0) and depends solely on temperature (T_0 and T) for isobaric conditions. From this budget, T_{ws} , the saturated temperature, is slightly warmer than T calculated in eq. 1 due to the W_s term. Similarly, the resulting air temperature (T_{air} , shown in Figure 1 above) will be slightly cooler than T_e (see eq.3) due to the W_s term.

$$T_{air} = T + \Delta T_Q - \left(\frac{W_s}{c_{p,cloud}}\right) \quad (11)$$

The differences between $T_{ws} - T$ and $T_0 - T_{air}$ are the same.

3) Invertibility of the energy budget of the saturated parcel

The invertibility of the energy budget for isobaric conditions relies on the fact that the total latent energy ($Q=dH$) can be expressed equivalently in terms of either LWC or the temperature difference ΔT between two saturated states. In Section 1, we show that the relationship between LWC and ΔT is one-to-one since the latent energy balance $L_v q_l = c_{p,cloud} \Delta T$, assuming $c_{p,cloud} = c_{pd} + c_{pv} r_s(T_0) + c_{pl} q_l$, can be uniquely solved in either direction. In this framework, this dependence is treated explicitly through an iterative solution, ensuring consistency between condensate and heat capacity.

In section 2, we show that the total energy is partitioned according to $Q = \Delta U + W_s$, where the internal-energy component $\Delta U = -c_{p,cloud}(T_0 - T_{ws}) = L_v q_{lws}$ defines a reduced cooling relative to the case without accounting for the W_s term. Despite this partitioning, the same functional dependence between q_{lws} and ΔT_{ws} is retained, ensuring that the mapping remains

one-to-one. Since the parameters at $W_{s, c_{p, cloud}}$ and L_v are calculated for the initial conditions of the parcel (T_0), the invertibility of the heat budget is conserved.

4) Calculation of liquid and water vapor supersaturation

Figure 1 above shows the effect of the partition of Q on the energy balance. The energy partition of S_c in the liquid phase (S_l) and vapor phase (S_v) is calculated based on the energy contributions of ΔU and W_s in the total energy of the saturated parcel (Q), respectively. S_l is considered for the liquid phase due to the vapor-liquid conversion, while S_v is associated with the water vapor expansion work.

The signs in the energy balance equations shown above describe the direction of energy transfer. However, S_l and S_v are not directional variables. They represent the partition of S_c considering the energy budget, which is defined from the absolute magnitudes of the energetic contributions, and thus, for a given latent heat released (Q), due to condensation S_l and S_v are calculated as follows:

$$S_v = S_c \cdot \frac{|W_s|}{Q} \quad [\%] \quad (12), \quad S_l = S_c \cdot \frac{|\Delta U|}{Q} \quad (13), \quad \text{and} \quad S_c = S_l + S_v \quad [\%] \quad (14)$$

The numerical differences while applying equations 1 and 8 to calculate Q are negligible ($< \sim 0.01\%$ on average).

5) Closure Analysis from in situ measurements

As described in the manuscript, the aircraft measured T , p , and LWC (or q_l) for cloud passes at growing convective cumuli (typically cumulus humilis and mediocris) with $N_d > 20 \text{ cm}^{-3}$ and positive vertical velocities. From these measurements, we calculate the energy budget and the S_c , S_l , and S_v of the parcel for the conserved heat (Q). In these estimates, we assume the cloud temperature equals the temperature of the saturated parcel (T in the schematic figure). In the first step, the values of T_0 are calculated iteratively based on the LWC from CDP and the meteorological measurements from BAHAMAS. In the second step, the energy budget is calculated, accounting for W_s , resulting in the values of S_l , S_v , and T_{air} .

We believe these clarifications address the reviewer's main concern and significantly improve the description of the derivations shown in the proposed manuscript. Below, you may find new figures that will be added to the main manuscript for clarity. Codes used in the calculations will be provided during the review process.

The description of the energetic budget and supersaturation calculations is provided in Section 2 of the revised manuscript. Due to the length of the derivation, we prefer not to reproduce it in this document. The codes used in the calculations are available in the shared folder at:

BRAGA, R. (2026). Manuscript Data: Energetic Derivation of Water Vapor Supersaturation at Cloud Base [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.20278305>

1. Validation

In Section 3.2, the authors compare inferred $N_d(S_v)$ at cloud base with $CCN(S_v)$ spectra measured below cloud base and concludes that they agree within uncertainty. First, how was the 10% uncertainty estimated/calculated/determined? Second, the authors note that the CCN measurements were taken roughly 700 m below cloud base in some flights and about 1400 m below cloud base in another, that CCN counters count droplets above $\sim 1 \mu\text{m}$ whereas N_d was measured for droplets larger than $1.5 \mu\text{m}$, and that spatial/temporal variability in hygroscopicity and turbulence can introduce additional uncertainty. I am afraid that those caveats really weaken the independence of the closure test. Agreement "within uncertainty" is encouraging but it is not yet a decisive validation of the thermodynamic interpretation. This appears to be more like an initial consistency check rather than a validation of the new supersaturation theory.

A: The reviewer considers that agreement between the theoretically derived estimates and those measured using instrumentation is a weak validation of the theory because of the inherent uncertainty in these measurements (explained further below), which were carefully considered and accounted for by the authors. While we agree with the reviewer that lower inherent uncertainties would be preferable, we argue that any impact due to the additional caveats mentioned are minor and that uncertainties of the range derived are common to all in-situ cloud microphysical measurements (whether acknowledged or not). We therefore propose that the validation is best practice that can be achieved with current airborne instrumentation, and that it provides a good initial validation of the theory proposed which might be further tested using a diverse range of in situ datasets by other researchers. We provide further updated information on the uncertainty analysis below.

The uncertainty shown in the figure relates to the measurement uncertainty of CCN and droplet concentrations (N_d). See item 3 for further information on the uncertainties of each set of measurements.

The comparison between $N_d(S_v)$ and $CCN(S_v)$ aims not only to check the measurement range but also to verify the robustness of the physical assumptions. Since S_v is a property of the gas (water vapor), the S_v from a CCN counter (CCN_c) is calculated based on the Kohler theory for particles with a known physicochemical composition, typically ammonium sulfate.

The $N_d(S_v)$ spectrum is representative of the $CCN(S_v)$ population below cloud bases that, after buoyant ascent, were activated into cloud droplets. Note that a smaller sample of N_d in comparison to CCN concentrations was measured in the time range in which the aircraft was at cloud base level (see Tables 2 and 3).

During the research flights, there is natural variability in CCN concentrations for a given measured S_v below cloud base. This variability is greater when flying within air masses affected by pollution plumes from biomass-burning and urban emissions. In the figure below (updated figure 5 in the former manuscript), the variability of the CCN population is observed in the measurements with fixed S_v (CCN_b), in this case, $S_v \sim 0.55\%$ shown in blue. The figure shows measurements of N_d in the same range of CCN concentrations for the same S_v . The measurements of CCN_a (shown in red) show cycling S_v between 0.2% and 0.55% every 100 seconds. Since some of the measurements below cloud base were affected by pollution plumes, the typical profile of $CCN(S_v)$ (i.e., CCN concentrations increasing with S_v) is not observed for all cases. This is clearly shown in the figure (e.g., in Flight AC11) where large concentrations were measured for relatively smaller S_v . In the flight

segment AC17b, a small variability of CCN concentrations is observed in the CCNb sampling, which results in CCNa(S_v) measurements more consistent with those observed in homogenous air masses.

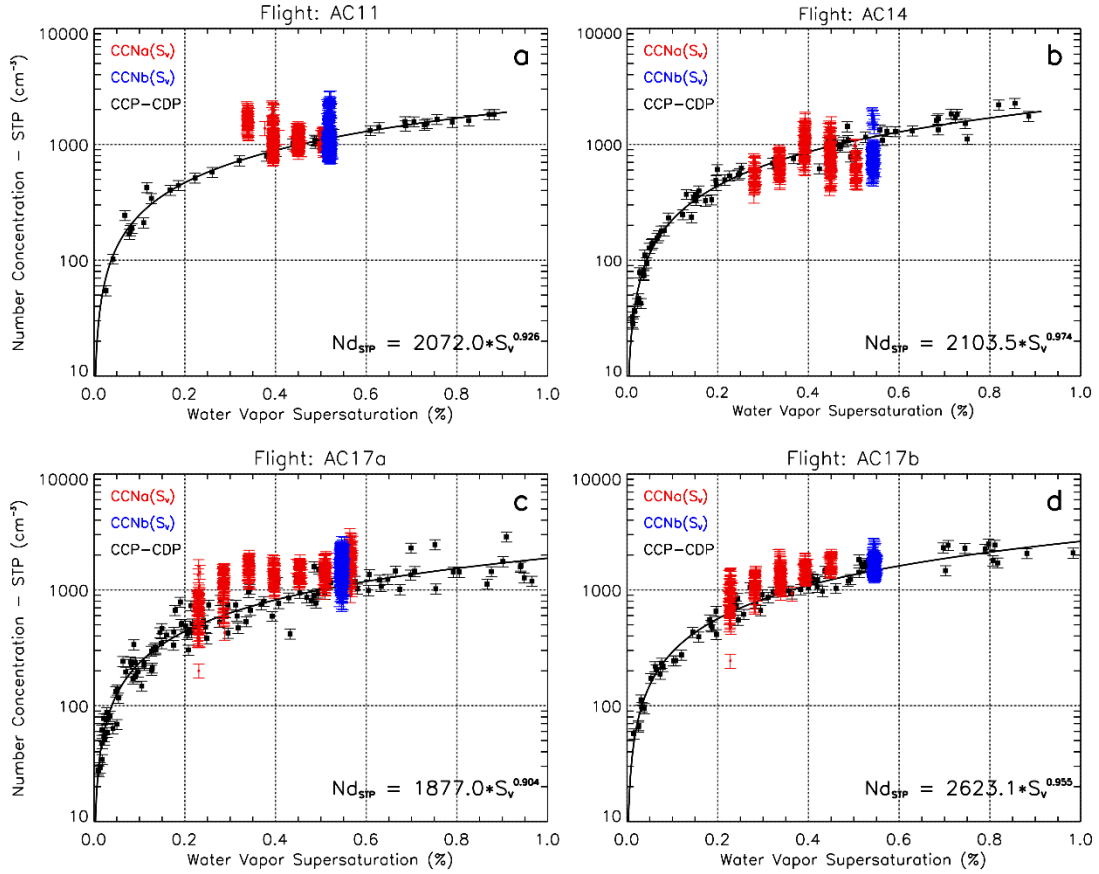


Figure 6 (former figure 5 updated). (a) S_v vs. N_d measured at cloud bases (black dots), and S_v vs. CCN concentrations measured below cloud bases (CCNa(S_v) in red and CCNb(S_v) in blue) during Flight AC11. N_d and CCN concentrations are calculated at standard temperature (0°C) and pressure (1013.25 hPa) (STP). Solid curves correspond to power-law fits of the form $N_d = C \cdot S_v^k$. (b), (c), and (d), similar data from flight legs AC14, AC17a, and AC17b, respectively. Error bars indicate the estimated uncertainties of N_d (10%) and CCN(S_v) concentrations (14%). Uncertainties of S_v from CCN counters (10%) and theoretically derived (12%) are not shown.

The figure below shows the $N_d(S_v)$ spectra and the CCN(S_v) measurements for time intervals in which both CCNa and CCNb had measurements, and the sampling was larger than 30 s. The CCN(S_v) measurements are shown with the same color for each cycle of CCNa measurements with fixed S_v . As mentioned before, a clear case of a pollution plume is identified in the flight AC11 data, where concentrations of up to 2000 cm^{-3} were measured in both CCN counters. The figure shows that most CCN(S_v) and $N_d(S_v)$ measurements lie within the uncertainty range, except for cases affected by pollution plumes. For clarity, the

uncertainties associated with the CCN(S_v) measurements are not shown in the figure. However, considering representative relative uncertainties of approximately 10% in S_v and 14% in CCN number concentration, the agreement between CCN(S_v) and N_d (S_v) remains within the combined uncertainty bounds, supporting the consistency of the closure analysis.

Spatial and temporal heterogeneity of the sampled air masses during flight segments AC11, AC14, and AC17a also contributes to deviations in the fitted relationships over specific supersaturation ranges (e.g., around $S_v \sim 0.55\%$ in AC14). In addition, discrepancies between inferred and measured values may arise from differences in the effective size detection ranges of the cloud droplet probe ($3 \mu\text{m} > d > 50 \mu\text{m}$) and the CCN counters ($d \geq 2 \mu\text{m}$), which sample distinct portions of the particle and droplet spectra.

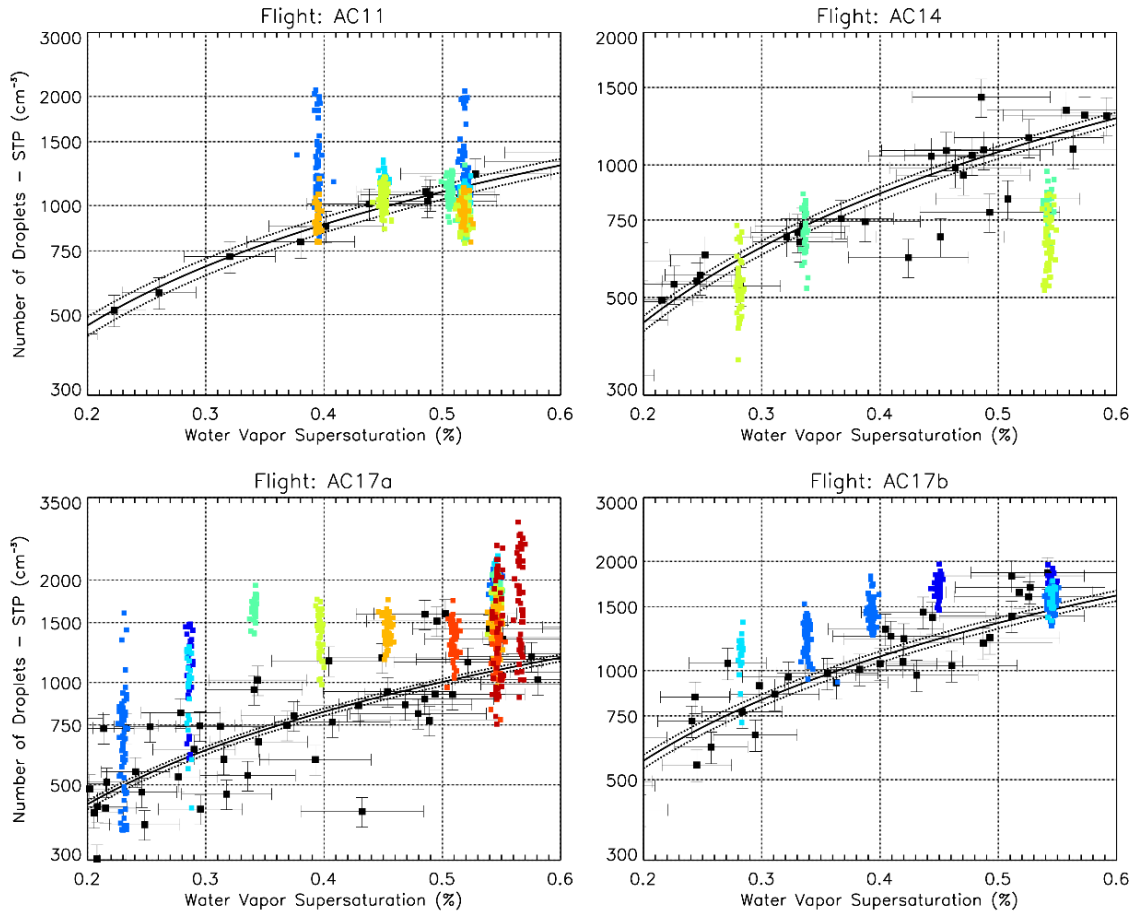


Figure 7 (new). (a) S_v vs. N_d measured at cloud bases (black dots); and S_v vs. CCN concentrations measured below cloud bases [CCNa(S_v) and CCNb(S_v)] for flight segments AC11, AC14, AC17a, and AC17b. CCN measurements are presented using consistent color coding for CCNa and CCNb, corresponding to each CCNa measurement cycle at fixed supersaturation (S_v). Each measurement period includes a minimum sampling duration of 30 s in both counters. Solid curves correspond to power-law fits of the form $N_d = C \cdot S_v^k$ (equations shown in the previous figure), dashed lines indicate the fit with $\pm 1\sigma$. N_d and CCN concentrations are calculated at standard temperature (0°C) and pressure (1013.25 hPa) (STP). Error bars indicate the estimated uncertainties of N_d and S_v , 10% and 12%, respectively. For clarity, uncertainties of CCN concentrations (14%) and S_v (10%) from CCN counters are not shown.

In the revised version of the manuscript, the discussion of the cloud-base and sub-cloud CCN measurements is presented in Section 3.3. Furthermore, the updated figures and the corresponding statistical analysis are included in the supplementary material.

1. Uncertainty analysis.

The manuscript reports uncertainties for measured and inferred variables in Sections 2.5.1, 2.5.4, and 3.2. Those numbers are helpful, but it is unclear how those numbers were obtained. It is also unclear which sources dominate the uncertainty in the inferred S_v . Please provide a more detailed sensitivity analysis of S_v to temperature and LWC uncertainties, etc.

A: We thank the reviewer for this comment. We agree that the original manuscript did not describe the uncertainty analysis with sufficient detail. The measurement uncertainties of temperature (± 0.5 K), pressure (3 Pa) from BAHAMAS data, and liquid water content (10%) from CCP-CDP are analyzed and described in our previous manuscript for the Amazonian flights (Braga et al. 2017) (<https://doi.org/10.5194/acp-17-7365-2017>).

We have contacted the CCN counter PI (Dr. Mira Pohlker) about the uncertainties regarding the flights we used in this manuscript. She updated us that the uncertainty in S_v remains 10%, but the CCN concentrations were recalculated in other analyses, and they end up at about 14% in these measurements (10% from counting efficiencies and 10% due to calibration accuracy). This will be described in the new version.

Following the calculations described in the previous section, the measurement uncertainties were propagated using a Monte Carlo approach, enabling a consistent estimation of uncertainties in both Step 1 - latent energy closure and Step 2 - energy partition. Uncertainties were propagated using a Monte Carlo approach (the code and the resulting analysis is available upon request for review). For each cloud pass (1Hz data), $N = 3000$ – 5000 realizations were generated by perturbing the measured inputs:

$$T_i = T + \delta T, p_i = p + \delta p, LWC_i = LWC \cdot (1 + \delta_{LWC}) \quad (14)$$

where perturbations were sampled from Gaussian distributions:

$$\delta T \sim \mathcal{N}(0, \sigma_T), \delta p \sim \mathcal{N}(0, \sigma_p), \delta_{LWC} \sim \mathcal{N}(0, \sigma_{LWC}) \quad (15)$$

For each cloud pass, the full thermodynamic calculation (Step 1 and Step 2) was recomputed. The uncertainty for each variable X was defined as:

$$\sigma_X = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (X_i - \bar{X})^2} \quad (16)$$

and the relative uncertainty in % was calculated with respect to the measured value:

$$\epsilon_x = \frac{\sigma_x}{X_{\text{nom}}} \cdot 100\% \quad (17)$$

We recalculate the uncertainties of the relevant variables (due to the change in the RHc equation) in this manuscript using this method. Uncertainties in the meteorological measurements from the BAHAMAS system translate into an estimated average uncertainty of about 0.24% (typically < 1% for 1 Hz data) in the derived RHc when calculating using the Bolton equation. The relative uncertainties of the energy terms were about 10% for Q and ΔU , and 13% for Ws. Propagating these errors yields overall uncertainties of ~10% for Sc and Sl, and ~12% for Sv. The numerical differences between the energy budget calculations performed in the first and second steps described in the section above were negligible (< ~ 0.01%) due to the invertibility of the latent energy budget.

The power-law relationship $N_d = C \cdot S_v^b$ was fitted for each flight using Monte Carlo uncertainty propagation (using 10% for N_d and 12% for S_v). Across all flights, the exponent is well constrained with uncertainties of $\sigma_b \approx 0.01$ –0.03, while the C shows relative uncertainties of approximately 2–6%. This indicates a robust determination of the N_d - S_v scaling despite measurement uncertainties. The code used for that can also be provided in case of review.

Braga et al.: Comparing parameterized versus measured microphysical properties of tropical convective cloud bases during the ACRIDICON-CHUVA campaign, *Atmos. Chem. Phys.*, 17, 7365–7386, <https://doi.org/10.5194/acp-17-7365-2017>, 2017.

In the revised version of the manuscript, we provide a more rigorous statistical analysis in response to your comment and the comments of Referee #2. This analysis is described in the new Section 2.7.3 and in the Supplementary Material.

2. The statement that adiabatic models overestimate LWC, buoyancy, and updraft speed. This is one of the manuscript's strongest claims. However, there is no direct comparison against results from other models. Please add such a comparison, either analytically or numerically, and identify exactly which governing-equation term convectional models omit. Otherwise this claim needs to be softened.

A: Indeed, this is not adequately covered by the content of the current manuscript and will be removed.

In the revised version, we softened this statement and included it only in the Conclusions section, as follows:

“...Within the proposed framework, neglecting the energetic cost of water vapor expansion (W_s) assigns a larger fraction of the available energy to vapor-to-liquid conversion. This suggests a possible tendency to overestimate condensate production, latent heating, buoyancy and associated updraft speeds in simplified parcel calculations that do not explicitly account for this energetic partition.”

3. Concepts/definitions.

- Cloud relative humidity RH_c

The authors introduced a new concept of relative humidity RH_c , and for a saturated parcel or cloud, $RH_c < 1$. I would argue that this is confusing to most readers, because RH for a saturated parcel is normally 100% by definition. I

suggest the authors to either rename RH_c to something like a "reference-state saturation ratio" or provide an earlier clarification/explanation of how it differs from conventional RH.

A: We agree with the referee. This was clarified above.

In the revised version, RH_c refers to the reference-state saturation ratio.

- Cloud supersaturation or cloud supersaturations

The authors first defined cloud supersaturation (S_c) at Line 102, then partitioned it into contributions from the liquid phase (S_l) and the vapor phase (S_v). But for many instances (e.g., Line 188,259), the authors used "cloud supersaturations"

and "cloud supersaturation" interchangeably, which is very confusing.

A: On reflection we can see how this would be confusing to the reader. We have corrected all instances to use the precise terminology in each case.

- ΔU , ΔU_{ws} and Q

In Table 1 and Eqs 18 and 19, ΔU_{ws} and ΔU appear to be 2 different variables as ΔU_{ws} includes W_s and ΔU does not. But in the caption of Figure 2, the author states " ΔU_{ws} (indicated as ΔU for simplicity)". This is very confusing. So which inferred variable is actually shown in Figure 2? Please clarify the difference

between ΔU_{ws} and ΔU .

Furthermore, if ΔU_{ws} already includes W_s , then what is the difference between ΔU_{ws} and Q ?

A: Indeed, the term ΔU in the first step of derivation (see equation 1 above) was removed and substituted by the enthalpy term (ΔH). We consider that the revised description above clarifies any ambiguity in the notation.

Enthalpy term is dH in the reviewed version.

- Cloud base

The authors need to provide a clearer definition of cloud base, especially for the aircraft analysis. Is it first nonzero LWC or other thresholds?

A: The theoretical calculations define cloud base when LWC exceeds 0 g m^{-3} . In the aircraft observations, cloud presence is identified using $N_d > 20 \text{ cm}^{-3}$, which in practice corresponds to an LWC $> \sim 0.01 \text{ g m}^{-3}$. This was stated as follows in section 2.4: “In this study, we focus on the initial stage of cloud formation, and thus, cloud passes with a number concentration of droplets (N_d) greater than 20 cm^{-3} , developing in updraft conditions, are considered.”

In the revised version of the manuscript, we provide a more rigorous statistical analysis in response to your comment and the comments of Referee #2. The Supplementary Material contains details about the cloud identification threshold used in our analysis (Section S2.1) and the effect of this assumption on the results.

4. The structure of the manuscript.

- Introduction

The Introduction is too short (at and before Line 50). It does not provide a thorough and comprehensive background/review of the research topic. The research motivation is unclear and objectives/questions vague. The cited studies are not up to date. Lines 51-79 (including Figure 1) should either go to Methods or at least be largely shortened.

A: We wished to respond quickly to the substantial technical critiques of our manuscript. In the updated manuscript we will provide an improved and extended review of the research topic in the introduction. Figure 1 will move to the Methods section.

The revised Introduction section (not shown here due to its length) substantially improves the clarity and scientific framing of the manuscript. In particular, it provides a more rigorous description of the physical basis of the proposed energetic framework, including a clearer discussion of the limitations of current approaches used to estimate cloud-base supersaturation, the role of Köhler theory and parcel models, and the motivation for introducing a thermodynamically constrained diagnostic method. The revised text also more explicitly distinguishes the proposed framework from conventional parameterization approaches by clarifying which variables are prescribed, measured, and diagnostically inferred from the cloud energy budget. In addition, the overall structure and logical flow of the Introduction were substantially reorganized to

improve readability and to better relate the theoretical formulation with the observational validation presented in the manuscript.

- Methods
 - Lines 98-115 can be largely shortened. This part seems repetitive of Lines 51-79.
 - I would suggest the authors merge Sections 2.1-2.3 into 1 shorter section and show only the very necessary definitions and equations, while other derivations can be more specific and moved into an appendix.
 - Section 2.4 mentions iterative estimation of T_0 and related quantities, I think the manuscript would really benefit from a compact algorithm summary: inputs, iteration sequence, criteria, and any quality-control filters applied to cloud passes. Doing so will not only make the proposed workflow more transparent but also benefit model implementation, as the authors noted many times in the paper.

A: We agree with these suggestions and will implement them in full as we revise the manuscript further.

We substantially revised Section 2 and clarified the methodology throughout the manuscript. We believe that the revised structure and presentation in the new version provide a more transparent and physically consistent description of the proposed framework and its underlying assumptions.

Section 2.5 can also be shortened. I appreciate that the authors provide uncertainties of the observations, but the authors did not state how these uncertainties were estimated/calculated.

A: We believe this comment is now addressed per section 3 of this response.

The updated statistical analysis is presented more clearly in the revised Section 2. Furthermore, we added an additional section to the Supplementary Material to provide further clarification and supporting analyses.

- Supplementary information
 - Figures S2-S8 are not just ancillary repetitions; they show that the claimed behaviors are robust across environments. This consistency is a strength, and the authors can be more explicit about it in the main text.
 - The simulations in S1 is also interesting and supportive of the results. It shows that the proposed framework behaves smoothly and systematically across temperature, cooling rate, and pressure, which is reassuring from an internal-consistency standpoint. I would suggest the author shorten the simulation analysis and move it to the main text, with a brief section in Methods describing the model configurations.

A: Agreed, we will reorganize the manuscript to clarify the method and include these results in the main text. Most relevant figures will be included.

The simulations previously presented in the Supplementary Material are now included in the main text in Section 3.1. In addition, the supplementary figures were updated to better demonstrate the robustness of the analysis across all flight segments and under different atmospheric conditions. We also added figures comparing the water vapor pressure simulated by the theoretical framework with that measured by the aircraft observations, further emphasizing the agreement between the modelled and observed thermodynamic properties.

5. Tables and figures.

- Figure 1: it is helpful to have a schematic figure. But Figure 1 is not clear enough. It mixes physical states, inferred states, and schematic arrows in a way that is difficult to interpret. Please state more clearly which temperatures are observed, which are hypothetical, and which follow from the closure assumptions.

A: Indeed, we apologize for this mistake.

The new Figure 1 is now presented and described in the Methods section as follows:

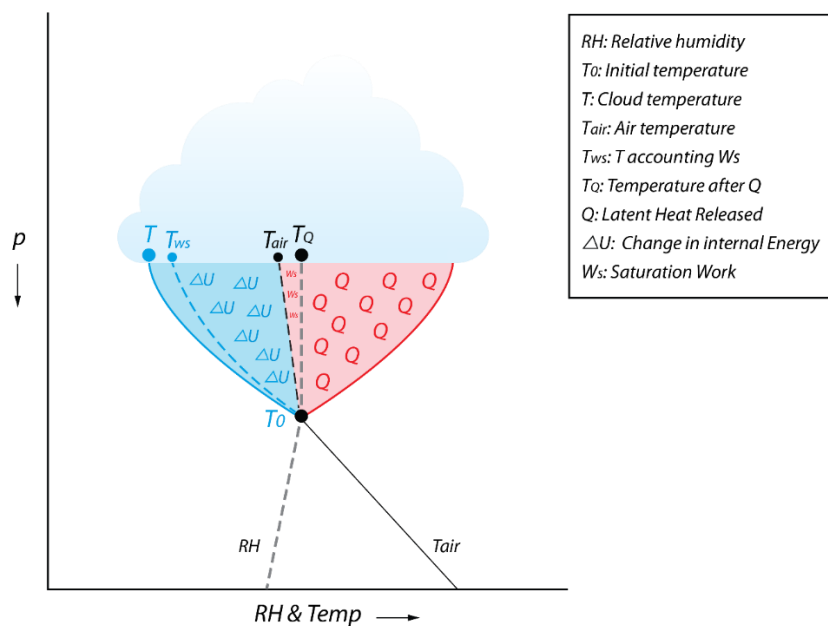


Figure 1. Energy balance of a cloud-adiabatic air parcel at cloud base under a local quasi-isobaric approximation. Below cloud base, the moist air parcel ascends due to buoyancy. T_{air} decreases with altitude while RH increases up to the saturation level of water vapor ($\text{RH} = 100\%$), where the temperature and pressure are T_0 and p_0 , respectively. Above this level, the ascending saturated parcel cools adiabatically as pressure (p) decreases slightly and the parcel reaches temperature T . For the local quasi-isobaric approximation used in the energy-budget calculation, the pressure variation across the analyzed cloud-base layer is assumed negligible relative to the ambient pressure. The total energy of the parcel is given by the latent heat released during condensation (Q), which is proportional to the enthalpy change resulting from the water vapor to liquid water conversion. From the first law of thermodynamics for isobaric conditions, the energy of the closed thermodynamic system Q is partitioned into the internal energy change (ΔU) and saturation work of water vapor (W_s). As a result, T_{air} is warmer than T and cooler than the temperature corresponding to the case in which water vapor is fully condensed (T_Q). When the W_s term is included, the effective saturated parcel temperature (T_{ws}) becomes slightly warmer than the purely expanded state, i.e., $T_{\text{ws}} >$

T. The energy expended on water vapor expansion (W_s) during this process results in an excess of water vapor (S_v) relative to the case of complete condensation. The Q region schematically mirrors the total energetic partition shown on the left-hand side of the figure.

- Figure 2: in panels a and b, there are no color legends.

A: Thanks, we added that.

The referred Figure 2 is now presented as Figure 4 in the revised version.

- Table 1 can be shown much earlier in the paper.

A: OK. This will be moved to the end of the introduction section.

We moved this table to the Appendix due to its length, in order to improve the readability and overall flow of the manuscript.

- Tables 2 and 3: it is helpful to have "period of measurements", but it would be more helpful to add a column for the sample size of data collected/analyzed. Perhaps the authors can also add a column to state the location of each flight, instead of repeating it many times in the main text. Suggested captions: ""Measurements at cloud bases ... " and "CCN measurements below cloud bases ... "

A: Figure S1 shows the map with locations. Table 2 shows the 'Period of measurements', this is the sample size of cloud measurements in seconds, the initial time, and the end time are shown in UTC. CCN measurements are continuous; this is why there are more samples.

We will improve the clarity here.

We kept the figure showing the map with flight locations in the Supplementary Material. The tables were also slightly revised to improve clarity and readability.

- Figures 3 and 4: if the 8 cloud segments are the same in Table 2 or 3, you don't have to list them out again.

A: The colors indicate flight IDs. We will improve the clarity here.

The previous Figure 3, which referred to the partitioning of S_c into S_l and S_v , was removed because this partitioning is now clarified in the new Section 3.1. Figure 4 was updated and is now presented as Figure 5, which contains scatter plots of N_d-S_c , N_d-S_l , and N_d-S_v , as recommended by the reviewer. The new Tables 3–5 contain the statistics of the fits.

- Figure 4 and Figures S10-S11: these figures show that N_d scales comparably well with all 3 supersaturations (S_c , S_l , and S_v), then the authors need to explain more carefully what is fundamentally gained by isolating S_v , beyond the fact that it can be

interpreted as the vapor-phase fraction of the total supersaturation in the proposed framework. In other words, if N_d can already be well constrained by the convective S_c , then why partition it into 2 different components? Also, I would suggest the authors just panel the three figures together, perhaps remove the power-law fits on each panel or put them in another table if the figure gets too crowded.

A: Thanks for the suggestions. We aim in this manuscript to quantify S_v since it is the only variable that can be compared with CCN counter measurements. We will clarify better the importance of our analysis and why we focus on S_v .

A new figure (Figure 5) showing the relationships between N_d - S_c , N_d - S_l , and N_d - S_v is now included, and the fit parameters are presented in Tables 3–5.

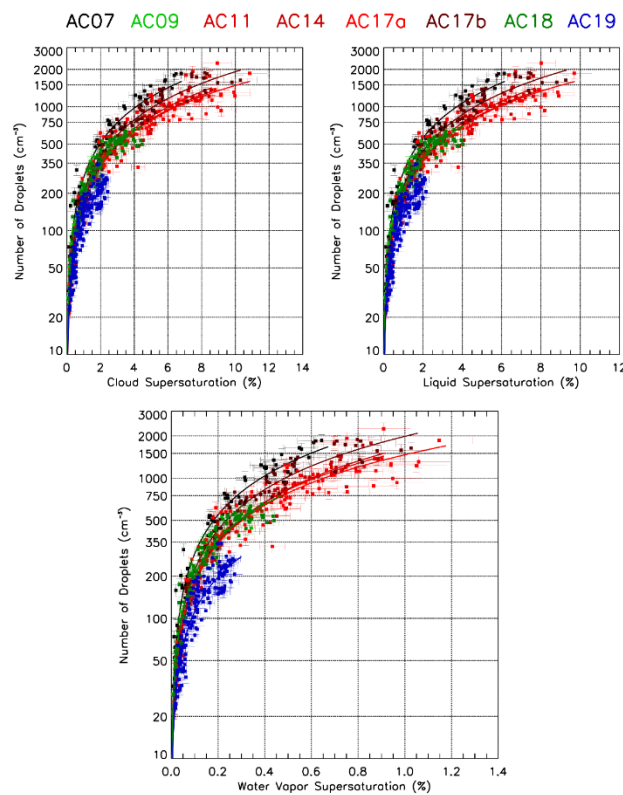


Figure 5. a) S_c vs. N_d for multiple flight segments (AC07, AC09, AC11, AC14, AC17a, AC17b, AC18, and AC19). Colored markers represent in-situ measurements, while solid curves correspond to power-law fits of the form $N_d = C \cdot S_c^k$. The colored markers correspond to different aerosol backgrounds in the Amazon region (red: Central Amazon, green: Northwestern Amazon, blue: Atlantic Ocean). b) and c) Similar for S_l vs. N_d and S_v vs. N_d , respectively. Error bars indicate the uncertainties of N_d (10%), S_c ($\sim 9.5\%$), S_l ($\sim 9.2\%$) and S_v ($\sim 12.6\%$). The statistics of the power-law fits are presented in Tables 3, 4 and 5.

- Figure 5: what's the difference between CCNa and CCNb? Where were they first defined?

A: These are the two CCNc counters (A and B), which we described above. We will clarify it better in the manuscript.

The new section 2.7.2 describes these measurements more clearly.

“During the ACRIDICON-CHUVA campaign, CCN number concentrations were measured at a frequency resolution of 1 Hz onboard HALO using a two-column CCNC [CCN-200; columns A (CCNa) and B (CCNb)], which is a continuous-flow longitudinal thermal-gradient instrument manufactured by Droplet Measurement Technologies (DMT) (Roberts and Nenes, 2005). In the instrument, the sampled aerosol particles are exposed to a set supersaturation and absorb water depending on their size and chemical composition. Particles that grow to droplets larger than 1 μm in diameter are counted as CCN at that S_v . CCNa measured CCN concentrations with cycled S_v between 0.2 and 0.55 % at 100 s intervals, and CCBnb measured CCN concentrations with a fixed $S_v \sim 0.55$ %. Table 2 summarizes the general thermodynamic conditions and the time intervals during which CCN measurements were conducted below cloud base. The $N_{\text{CCN}}(S_v)$ measurements of the chambers was compared to the measured N_d and calculated S_v for three flights where $N_d(S_v)$ and $N_{\text{CCN}}(S_v)$ had the same range of S_v values.

For measurements on polluted conditions during flights AC11, AC14 and AC17, the estimated uncertainties in CCN concentrations are about 10%. Furthermore, the estimated uncertainty in S_v values is about 14% on average, resulting from the uncertainties of 10% from counting efficiencies and 10% due to calibration accuracy. Sample air for the aerosol measurements was obtained from two different inlets: (i) the HALO aerosol submicron inlet (HASI) and (ii) the HALO counterflow virtual impactor (HALO-CVI). The CCN-200 provides the possibility to measure from both inlets in parallel or at two different values of S_v .”

The manuscript needs a cleaner separation between what is observed, what is retrieved, and what is assumed. This distinction should be explicit throughout the manuscript and especially in the figure captions and conclusions.

A: We agree with the referee. We believe the information provided above clarifies the manuscript's message.

Minor comments:

1. Line 16: "We find that ...". Did you really "find" that? Or you derived/speculated/assigned that? A: Derived...we changed in the new version.
2. Line 29: with respect to "liquid water" or "water vapor"? A: liquid water. The statement is correct.
3. Lines 38-39: are there more recent studies? A: We will add new references about this topic. The new version provides a better introduction with additional references.
4. Line 41: N_d is first defined here. Please use N_d in the reminder of the paper, no need to state "droplet number concentrations" again, e.g., Lines 262 and 341. A: Ok.
5. Line 45: "the activation" of what? A: "...CCN particles..."
6. Lines 45-47: "Even though ...". So? What is the issue or challenge here? A: The whole challenge is that S_v is not measured with accuracy in clouds. Current airborne relative humidity instrumentation has uncertainties of about 5% in cloud. Thus, S_v is an estimate based on model assumptions, which presents variability depending on the atmospheric conditions and particles hygroscopicity. In this manuscript, we provide a new method for S_v calculations based only on the thermodynamic of the cloudy parcel. This will be better clarified in the new version of the manuscript.
7. Line 54: 10^{-3} Pa? hPa? A: hPa...thanks
8. Line 61: where is P_0 in Figure 1? A: P_0 is assumed the same as P as described in line 54.
9. Line 65: $C_{p,cloud}$ is not defined yet. A: We moved that figure to methods.
10. Line 98: remove "at cloud base". A: Ok...thanks.
11. Line 100: add "cloud" before "relative humidity", if the authors decide to keep using this name. A: Ok...thanks.
We changed it to refence-state of saturation, as described above.
12. Line 102: determine"s". A: Ok.
13. Lines 118-119: Please rewrite this sentence, it is difficult to read. Perhaps "The formulation of RH describes the amount of water vapor in the air relative to the maximum amount of water vapor the air can hold for a given temperature ...". A: Ok.
14. Line 123: How is this minor uncertainty estimated/calculated? A: This is from laboratory measurements.

The stated $\sim 0.1\%$ uncertainty refers to the approximation error reported for the Bolton (1980) empirical saturation vapor pressure formulation relative to reference formulations, not to an uncertainty estimated from our measurements.

15. Lines 134-135: cooling can not exceed the rate of condensation. I assume the authors meant "cooling rate initially exceeds the rate of condensational heating"? A: yes thanks.
16. Please rewrite Lines 143-144, if the authors decide to keep it. This sentence is difficult to follow. A: Ok. We will provide better wording.
17. Line 150: the specific volume of water vapor is defined as " α_v ", but in Eqs 6, 10, and many other instances, it is written as αv . A: Ok. We will fix that.
18. Line 162 and Eq 9: it is unclear to me how the authors arrived from Eqs. 1, 4, 5, and 6 to Eq9. A: This derivation is removed from the manuscript...see comments above.
19. Line 165: by "a reference level", you mean "the cloud base"? A: initial temp. T0
20. Eq10: again, it is confusing to me how the authors arrived from Eq 9 to Eq 10. A: Te is the same in this case...this derivation is removed from the manuscript.

21. Line 170: density is an intensive property; it doesn't get lost by condensation like mass or number concentrations. I notice that term "vapor density" is used many times in the manuscript, perhaps the authors should also provide the definition. A: vapor density is the inverse of $\alpha_v=1/\rho_v$.
22. Lines 188-189: change to "where temperature gradients typically are smaller than 1K". A: in our analysis from cloud base measurements the maximum temperature gradients were about 1 K.

Erratum: the maximum temperature gradient, or adiabatic cooling, was 2 K in the simulations and ~1.8 K in the measurements.

23. Line 189: the calculation "s", and by "cloud supersaturation" you mean S_c ? A: Yes.
24. Lines 190-192: please rewrite this sentence. A: Ok.

This sentence was removed.

25. Line 226: please be consistent with the temperature forms. A: Ok...we will improve that.
26. Line 228: how is T_0 estimated? A: We described it above.
27. Line 236: by "these microphysical processes", you mean "expansion, condensation, and latent-heat release"? If so, I think only condensation here is a microphysical process. Expansion, either air parcel or water vapor, is more a thermodynamic process; and latent-heat release is a thermodynamic consequence of a phase-change microphysical process.
A: We agree.

This paragraph was removed.

28. Line 237: this is already the third appearance of "for modeling purposes". And here, do the authors refer to any specific model or all numerical models? A: Adiabatic cloud microphysical models.
29. This paragraph was removed.

30. Lines 243-244: what does this sentence mean? A: We better described it above.
31. Line 261: I think Table 2 just provides basic atmospheric conditions (same comment for Table 3). And which "cloud properties" were measured at cloud bases? A: The tables provide the general atmospheric conditions during the measurements. CCP measured the DSDs from 3-960 micron. The relevant measurements to our study are N_d and LWC. We will clarify that in the new version.
32. Lines 262-263: "cloud passes ... developing in updraft conditions". Please rewrite this sentence. Clouds can develop in updraft conditions, cloud passes can not. Plus, was the updraft also measured during flights? How strong updraft speeds are considered? A: This is described in section 2.5.1. The histogram with updraft velocities are shown in the supplementary material.

We refined this discussion in the new section 2.6 as follows:

“The calculations of RH_c and cloud supersaturations (S_c , S_i , and S_v) at cloud bases are performed using measurements from cloud probes and meteorological sensors on board of HALO. Table 1 summarizes the general thermodynamic conditions and time intervals of cloud properties measured at cloud bases. The cloud measurements were conducted with the Cloud Combination Probe - Cloud Droplet Probe (CCP-CDP) (Lance, 2012). In this study, we focus on the initial stage of cloud formation. Therefore, only 1 Hz cloud passes (individual in-cloud sampling intervals) with N_d greater than 20 cm^{-3} , developing under updraft conditions, are

considered. This threshold of $N_d = 20 \text{ cm}^{-3}$ is used to avoid haze and well-mixed cloud elements in the analysis. Furthermore, cloud passes with measured raindrops are removed from our analysis. In the supplementary material (Section S2), we present the sensitivity analysis assuming the proposed threshold for cloud identification and varying the values of N_d and LWC for the derived supersaturations and their relationships. These analysis shows that the derived supersaturations and their relationships assuming the proposed threshold ($N_d > 20 \text{ cm}^{-3}$) are robust with respect to variations in cloud identification criteria. The remaining variability is primarily driven by environmental heterogeneity and turbulence rather than by the threshold definition itself.”

Furthermore, we added a discussion in the revised version of the manuscript at section 3.2 describing the vertical velocities observed during the flights. The new Figure S19 presents the vertical velocity measurements for each analysed 1 Hz cloud pass.

“The cloud properties observed under CCN-limited regimes were generally associated with regions of weaker buoyant forcing, resulting in lower LWC and weaker w , with maximum values $\sim 2 \text{ m s}^{-1}$ (Figure S19). In contrast, aerosol-rich environments were associated with stronger buoyant forcing and enhanced adiabatic cooling at cloud base, leading to larger LWC, higher S_v , and stronger w (up to $\sim 4 \text{ m s}^{-1}$). Enhanced buoyant forcing also increased the variability of cloud-base measurements by strengthening fluctuations in the thermodynamic state of the cloud parcel (LWC, T , and p), which are the primary variables used in the energy budget and supersaturation calculations. However, the uncertainties in S_v do not scale directly with buoyant forcing itself, but rather with the uncertainty in these thermodynamic and microphysical measurements (see Section S2.2). Consequently, the largest observed S_v and w values were generally associated with larger cloud base LWC values, consistent with stronger adiabatic cooling and enhanced condensational growth.”

33. Line 270: remove "measured". The authors need to be more clearly stating which variables are inferred, which are calculated, and which are measured. [A: Ok. Thanks.](#)
34. Step 2 around Line 270: did the authors calculate/estimate T_{ows} from a given $|V_s|$? Or did the authors calculate/estimate $|V_s|$ from T_{ows} ? This is unclear to me. And this step is difficult to follow. [A: We better described it above.](#)

We provide a new description of the closure analysis in the revised manuscript:

“The closure analysis relies on the reversibility of the cloud adiabatic parcel as described in section 2.4. The calculations of RH_c , S_c , S_l , and S_v require the information of p , LWC, T , and T_0 near cloud bases. From the airborne data at cloud bases, p , T and LWC are measured. Therefore, we estimate T_0 and T_{air} for each cloud pass. Below are the sequential steps used in our analysis:

1. T_0 (or T_Q) is iteratively estimated for each cloud pass from Q (calculated from LWC, T and p) using Eq. 16.
2. RH_c and S_c are subsequently calculated from T and estimated T_0 .
2. The process is repeated by considering both Q , calculated in the first step, and W_s in the energy budget (see Eq. 16), which results in an estimated air temperature (T_{air}) lower than T_0 obtained in step 1, such that $T_0 > T_{\text{air}} > T$. From this closure analysis, the values of ΔU and W_s are estimated, and S_l and S_v are subsequently calculated with Eqs. 18 and 19, respectively.”

35. Lines 278-279: which is measured by SHARC? Which is derived? [A: Mixing ratio of water vapor.](#)
36. Line 283: define CCP. [A: Ok.](#)
37. Line 293: cloud base"s". [A: Ok.](#)
38. Line 298: remove "water vapor supersaturation". [A: Ok.](#)
39. Line 299: "... exposed to a set supersaturation", you mean S_v ? [A: Yes.](#)
40. Line 308: remove "rain water content". [A: Ok.](#)
41. Remove Lines 337-340, this is redundant. [A: Ok.](#)
42. Line 341: perhaps provide one-sentence justification for this specific case. And remove "droplet number concentrations", you have defined it earlier. [A: Ok.](#)

Below is the new text:

"Figure 4 illustrates a case study of the dependence of N_d at cloud base on RH, RH_c , cloud supersaturations (S_c , S_i , S_v), and the associated energetic terms (Q , ΔU , W_s) derived from measurements collected during Flight AC14. During this flight leg, cloud bases of developing cumuli were sampled under RH conditions ranging from $\sim 60\%$ to $\sim 102\%$, at an altitude of about 1600 m and temperatures near 17.6°C ."

43. Line 344: remove "(in black)". [A: Ok.](#)
44. Line 344: is each dot a cloud pass? [A: 1 Hz data.](#)
45. Lines 345-347: "This variability arises ...", again? [A: Ok...removed that.](#)

This content was retained in this section and removed from the previous sections.

46. Line 347: remove "(in red)". [A: Ok.](#)
47. Line 352: what do you mean by "cloud elements"? and how were "stronger buoyancy and more vigorous condensational growth" inferred? [A: Here, 'cloud elements' refers to localized in-cloud 1 Hz sampling volumes along the flight track. 'Stronger buoyancy' is not directly measured but inferred from updraft velocities shown in the supplement \(Fig.S9\). 'More vigorous condensational growth' is inferred from higher supersaturation \(\$S_v\$ \) and increased liquid water content.](#)

Vertical velocities are shown in Fig. S19 in the new version.

48. Lines 353-354: by "cloud supersaturation", you mean S_c ? or which one? [A: The sentence refers to the results in figure 2.](#)

Water vapor supersaturation (S_v). The new text in the manuscript states the following:

"...Conversely, cases in which $RH > RH_c$ indicate that the parcel retains a larger vapor content relative to theoretical calculations, favouring continued condensational growth, enhanced S_v , yielding higher N_d for a given CCN population."

49. Line 367: what kind of simulations? [A: We explored our calculations for a range of cooling rate and initial temperature. This is shown in the supplement \(Section S1\). The results of the updated](#)

simulations are shown above.

We added a new section 3.1 in the manuscript describing the simulations.

50. Lines 393-395: how was the "buoyant forcing" measured/inferred? The first sentence reads to me like "because there are lower LWC and updraft speeds in CCN-limited regions, so there is weaker buoyant forcing". But then the next sentence reads like "in polluted regions, because there is stronger buoyant forcing, so there are more droplet formation (so higher LWC?) and higher updraft speeds". The authors need to be more careful and clearer with these statements.

A: Buoyant forcing is not directly measured but inferred from updraft velocities shown in the supplement...Figure S9.

See the response in red about the buoyancy forcing at the previous page.

51. Line 405: how does the cooling of the cloud parcel reflect the relationship between LWC and Nd? A: We described it in section 2.2. A better explanation is shown above.

This sentence was removed and is now discussed in Sections 3.1 and 3.2 of the revised manuscript.

52. Lines 412-421 can be largely shortened. This part could have been stated in Methods. A: Ok. Thanks

53. Line 426: I am not sure if the Nd and CCN spectra comparisons "were within uncertainty range". For Flight 17 (Figure 5 c and d), the CCN spectra is above the Nd spectra.

A: better explanation is shown above.

Line 434: is there really an improved agreement for Flight 17? A: A better explanation is shown above.

Line 440: what do you mean by "appears reliable"? and please check the grammar and rewrite this whole sentence. A: Indeed, it is strange we will provide better wording in case of review.

Line 455: which "both cases"? A: The S_v from our calculations and those from CCN counters. We will provide better wording in case of review.

Below is the updated 1st paragraph included in the Conclusions section:

"... In both cases, the water vapor pressure results from a thermal gradient under saturated conditions. In CCN counters, S_v is produced within a continuous-flow chamber by imposing controlled temperature gradients (warmer downstream) along wet walls. These gradients promote differential diffusion of water vapor and heat, leading to an enhanced water vapor pressure along the flow axis that exceeds saturation at the local air temperature. In the proposed diagnostic framework, the S_v inferred from cloud base measurements represents the vapor-phase contribution to cloud supersaturation resulting from adiabatic cooling and is associated with the fraction of the latent energy partitioned into water-vapor expansion work (W_s) during the condensational growth."

54. Lines 472-473: were those lapse rates used anywhere in Section 2? A: This is shown in the updated figure and discussions above.

Indeed, the lapse rates were not explicitly discussed in the energetic calculations described in Section 2. In the revised manuscript, we instead suggest this as a possible direction for future research, as follows:

"... Furthermore, the thermodynamic evolution of cloudy parcels can be investigated within the context of the energetic budget to infer S_v from the vertical profiles of air temperature and dew-point temperature, with the parcel evolution physically interpreted in terms of dry- and cloud-adiabatic cooling..."

Lines 473: "Our results suggest...", which part of results or figure exactly? A: Our results show that the LWC is overestimated when W_s term is neglected in the calculations of energy budget. We will provide better wording in case of review.

In the revised version of the manuscript, we show this in Fig.S1 for 950 hPa and in Fig. S2 for 850 hPa. This discussion is also presented in our reply to Referee #2 (item 5).

Response to Referee #2

Dear Referee,

We sincerely appreciate your careful and constructive review of our manuscript. We are grateful for the time and effort you invested in evaluating our work. Your comments have been valuable in helping us improve both the clarity and robustness of the analysis.

We appreciate your summary of the manuscript and your recognition that the overall structure and presentation are clear. We acknowledge your concerns regarding aspects of the analysis that required further clarification. Accordingly, we have carefully addressed each of your comments in detail. The revised manuscript will include:

- Effect of background buoyant forcing in S_l and S_v regardless of aerosol regimes.
- An expanded statistical analysis in the Supplement, including uncertainty quantification and sensitivity tests of the cloud detection thresholds, to better support the $N_d - S(S_c, S_l, S_v)$ relationship.
- A more explicit treatment of the energetic contribution of W_s in the calculation of LWC at cloud base.

We believe that these revisions adequately address your concerns and improve the manuscript to a level suitable for publication.

General comments:

The paper presents a new method that employs the energy budget analysis framework to estimate the amount of supersaturation at warm cloud base by assuming the saturated parcel ascent as reversible adiabatic process with conserved isobaric enthalpy. The authors partition the supersaturation of the cloud (S_c) into vapor-phase (S_v) and liquid-phase (S_l) supersaturations to derive magnitudes of S_c , S_v , and S_l in the context of the energy balance defined by the first law of thermodynamics. This method is complemented by a closure analysis conducted using airborne observations of warm cumulus clouds from the ACRIDICON-CHUVA campaign. The analysis demonstrates how droplet number concentration (N_d) scales with S_v and agrees within the uncertainty range of CCN(S_v) spectra measured below cloud base prior to cloud observations.

Overall, the manuscript is well written and easy to follow. However, some analyses require further clarification. It is recommended that the manuscript be reconsidered after a major revision.

Specific Comments:

1. In section 3.1, please clarify the impact of background buoyant forcing on the estimated values of S_l and S_v using this framework regardless of aerosol regimes. In other words, how do uncertainty in S_l and S_v scales with increasing background buoyant forcing in any given environment?

A: We thank the referee for this important comment.

Background buoyant forcing primarily affects the dynamical evolution of the cloud base parcel, particularly the updraft velocity (w) and the associated cooling rate during ascent. Stronger buoyancy leads to faster adiabatic cooling and enhances the S_v generated along the parcel trajectory at cloud bases (Khain and Pinsky, 2018; Twomey, 1959). However, in the present study, S_l and S_v are not calculated based on the updraft velocity or the aerosol regime. Instead, they are diagnosed from the local thermodynamic state at cloud base and defined as the fractional contributions from the total latent heat release during condensational growth (Q), $\Delta U/Q$ and W_s/Q , respectively. As a result, background buoyant forcing does not directly impose a systematic shift in the relative partitioning between S_l and S_v . For a given thermodynamic state (T , p , LWC), the total energy Q is constrained by the enthalpy change ($dH = Q$), and the partitioning depends primarily on the balance between internal energy change and expansion work. The influence of buoyant forcing is therefore implicit, acting through its influence on the observed cloud base properties.

The figures below show the observed relationships between w , S_v , and S_l for the analysed flights. Since w is dynamically associated with parcel buoyancy, stronger updraft velocities produce increased spread and variability in S_v and S_l , particularly in updraft-limited (CCN-rich) regimes (e.g., during flight AC07), whereas in CCN-limited regimes the sensitivity to w is weaker (e.g., during flight AC19). Thus, the buoyant forcing primarily modulates the pathway to the cloud-base thermodynamic state rather than the thermodynamic constraint governing the energy partitioning applied in this study.

As discussed in Braga et al. (2017), and originally noted by Twomey (1959), although N_d is expected to increase with w in an idealized framework, in situ measurements exhibit substantial scatter due to turbulence. Individual cloud parcels ascend as turbulent eddies with locally varying w , and their subsequent mixing within the cloud introduces a large stochastic component to the observed relationship between w and microphysical properties. As a result, the correlation between w and quantities such as N_d and S_v is often weak, even though the underlying physical dependence remains valid.

Regarding uncertainty, increasing background buoyant forcing tends to enhance variability in cloud base measurements due to stronger vertical gradients in temperature, water vapour, vertical velocity, and droplet concentrations, as well as enhanced turbulence and sampling heterogeneity. This can lead to increased variability in LWC, T , and p , which are the key measurement inputs to the energy budget. However, the uncertainty in S_l and S_v does not scale directly with buoyant forcing itself, but rather with the uncertainty in these measured thermodynamic variables. In our analysis, the propagated uncertainties of S_l and S_v are on average $\sim 9.2\%$ (8.6 - 9.4%) and $\sim 12.6\%$ (12.3 - 13.2%), respectively, and are dominated by uncertainties in LWC, with secondary contributions from temperature and pressure.

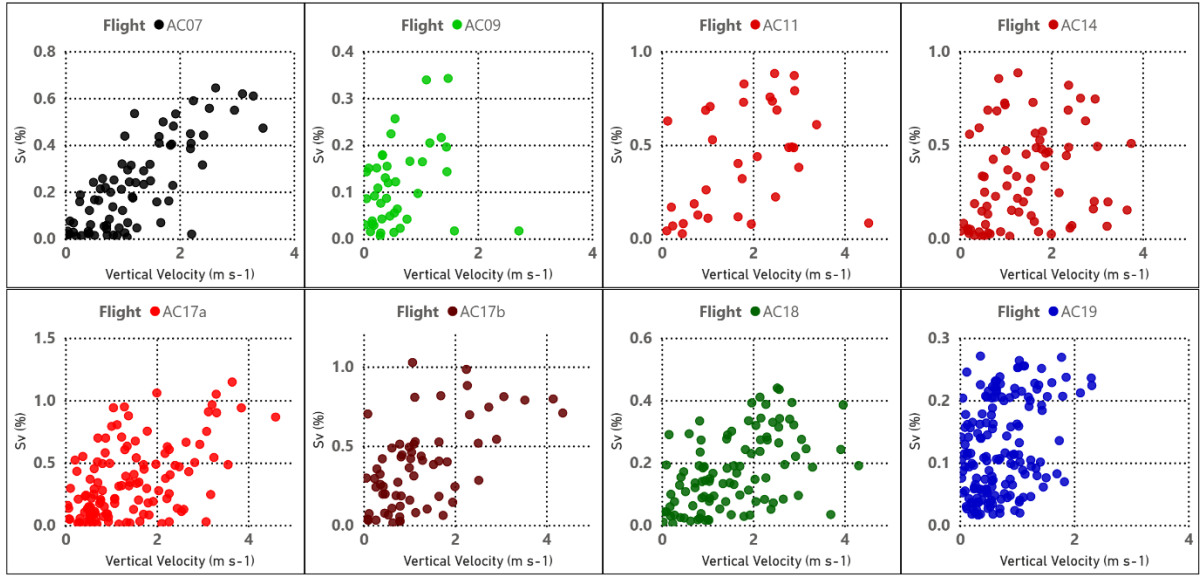


Figure R1. Vertical velocity vs. water vapor supersaturation (S_v). Flight segments are indicated in the legend.

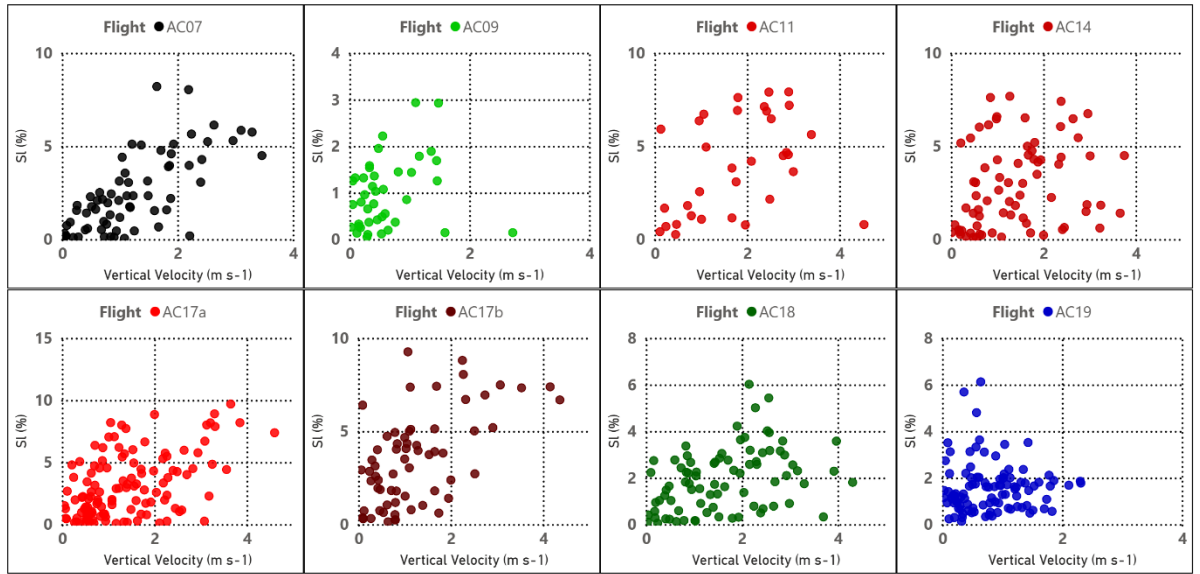


Figure R2. Vertical velocity vs. liquid supersaturation (S_l). Flight segments are indicated in the legend.

We added a discussion (see below) in the revised version of the manuscript describing the effect of background buoyant forcing in the results Section 3.2. In addition, the new Figure S19 presents the vertical velocity measurements as a function of S_v for each analysed cloud pass.

“The cloud properties observed under CCN-limited regimes were generally associated with regions of weaker buoyant forcing, resulting in lower LWC and weaker w , with maximum values ~ 2 m s $^{-1}$ (Figure S19). In contrast, aerosol-rich environments were associated with stronger buoyant forcing and enhanced adiabatic cooling at cloud base, leading to larger LWC, higher S_v , and stronger w (up to ~ 4 m s $^{-1}$), which more effectively promoted droplet activation. Enhanced buoyant forcing also increased the

variability of cloud-base measurements by strengthening fluctuations in the thermodynamic state of the cloud parcel (LWC, T, and p), which are the primary variables used in the energy budget and supersaturation calculations. However, the uncertainties in Sv do not scale directly with buoyant forcing itself, but rather with the uncertainty in these thermodynamic and microphysical measurements (see Section S2.2). Consequently, the largest observed Sv and w values were generally associated with larger cloud base LWC values, consistent with stronger adiabatic cooling and enhanced condensational growth.”

2. Cloud passes were considered using a threshold criterion of N_d greater than 20 cm^{-3} at initial stage of cloud formation (Lines 260-265). Since such in-cloud measurement thresholds are currently not standardized in our community, please perform sensitivity analysis on the resulting supersaturations with different threshold criteria defined using a combination of both minimum N_d and/or LWC. Additionally, please verify whether such definitions have any significant impact on the correlation coefficients discussed with power-law fits in Figure 4, S10, and S11. Include the analysis in the supporting information document.

A: Thanks for this comment.

In our previous manuscript (Braga et al., 2017), we had performed cloud base closure analysis using CCP-CDP and CAS-DPOL probes' data from the ACRIDICON-CHUVA campaign. Given the higher accuracy of the CCP-CDP probe from this analysis, we used the probe data in the current study. After several discussions with co-authors (CCP-CDP and CAS-DPOL probes' PI) about the suitable threshold for both probes, we agreed to apply the threshold of $N_d > 20 \text{ cm}^{-3}$ and $w > 0 \text{ m s}^{-1}$ for cloud bases of growing convective cumuli in clean and polluted conditions. This threshold prevented the detection of haze particles and cloud elements during the dissipating stage while calculating parameters relevant to cloud formation.

The cloud supersaturations calculated in this study are sensitive to LWC measured by CCP-CDP. The threshold we applied for cloud identification, in practice, corresponds to an $\text{LWC} > \sim 0.01 \text{ g m}^{-3}$, as shown in the figures below.

To address the reviewer's request, we performed a sensitivity analysis of the derived supersaturation components (S_c , S_l and S_v) using a range of cloud identification criteria based on varying thresholds of N_d and LWC. The results are summarized in Tables S1-S3.

Overall, the analysis shows that:

The correlation coefficients (R^2) of the power-law fits ($N_d = C \cdot S^k$) are generally insensitive to the choice of threshold and remain comparable to those obtained using the baseline criterion ($N_d > 20 \text{ cm}^{-3}$).

- For most flight segments, variations in threshold produce only minor changes in the fitted parameters (C and k), which remain within the estimated uncertainty ranges.
- A notable exception occurs for flight AC07 (polluted conditions), where lower N_d ($< 20 \text{ cm}^{-3}$) thresholds introduce increased variability and reduce correlation strength, likely due to inclusion of transitional particles.
- In contrast, for the cleanest case (AC19), slightly improved correlations are obtained when including lower N_d values ($< 20 \text{ cm}^{-3}$), consistent with relatively reduced CCN and buoyancy variability during cloud formation.

These results show that the derived supersaturations and their relationships, assuming the proposed threshold ($N_d > 20 \text{ cm}^{-3}$), are robust to reasonable variations in cloud identification criteria. The remaining variability is primarily driven by environmental heterogeneity and turbulence rather than by the threshold definition itself. All sensitivity analyses will be included in the Supporting Information (similar to what is shown at the end of this document).

The updated statistical analysis is presented more clearly in the revised Section 2.7.3. Furthermore, we added an additional section (S2.1) to the Supplementary Material to provide further clarification and supporting analyses.

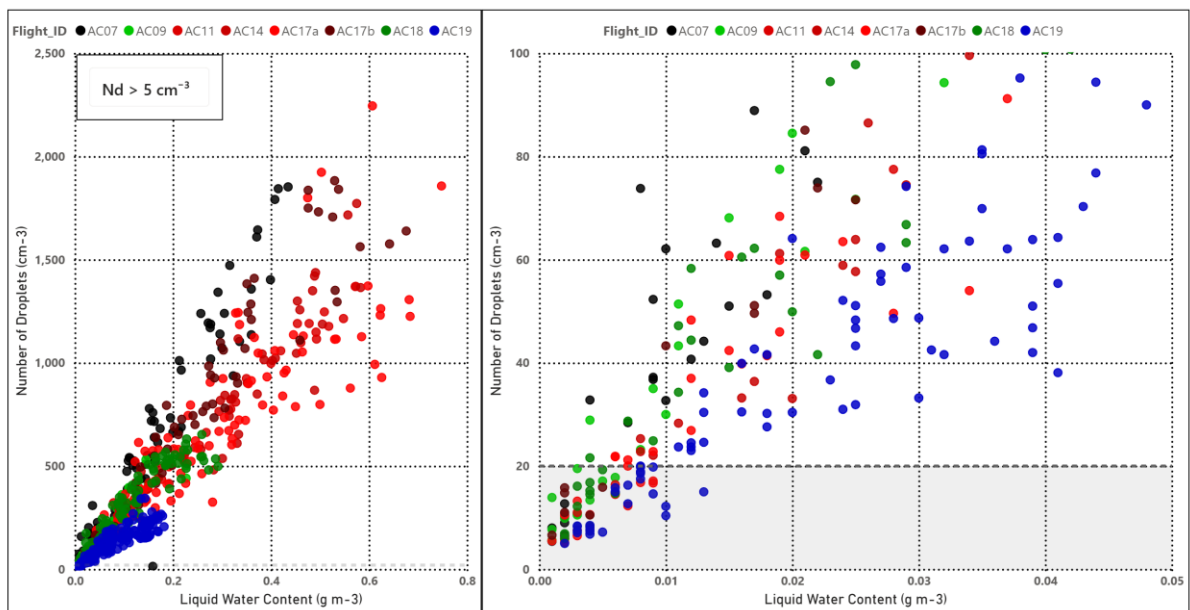


Figure R3. [left] LWC versus N_d for all flight segments. [right] Similar for ($N_d < 100 \text{ cm}^{-3}$ & $\text{LWC} < 0.05 \text{ g m}^{-3}$). The threshold $N_d = 20 \text{ cm}^{-3}$ (dashed line) corresponds approximately to $\text{LWC} \gtrsim 0.01 \text{ g m}^{-3}$ for most flights' data. The shaded region shows the excluded 1 Hz cloud passes for the adopted criterion ($N_d > 20 \text{ cm}^{-3}$).

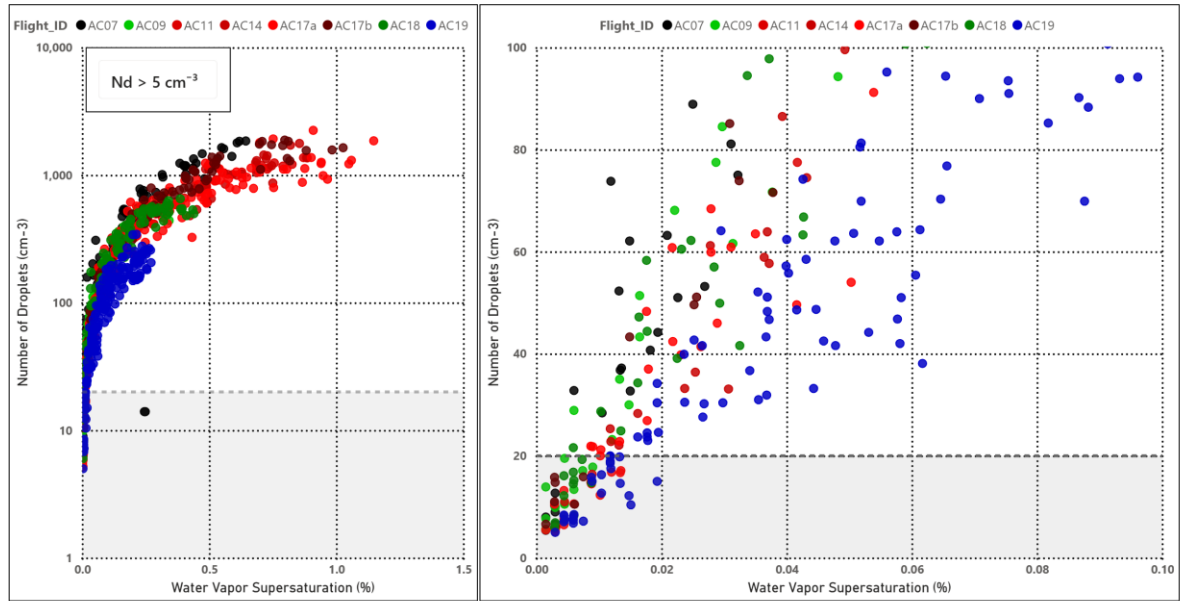


Figure R4. [left] water vapor supersaturation (S_v) vs. N_d for all flight segments ($N_d > 5 \text{ cm}^{-3}$). [right] Similar for ($N_d < 100 \text{ cm}^{-3}$ & $S_v < 0.1 \%$). The shaded region shows the excluded 1 Hz cloud passes for the adopted criterion ($N_d > 20 \text{ cm}^{-3}$).

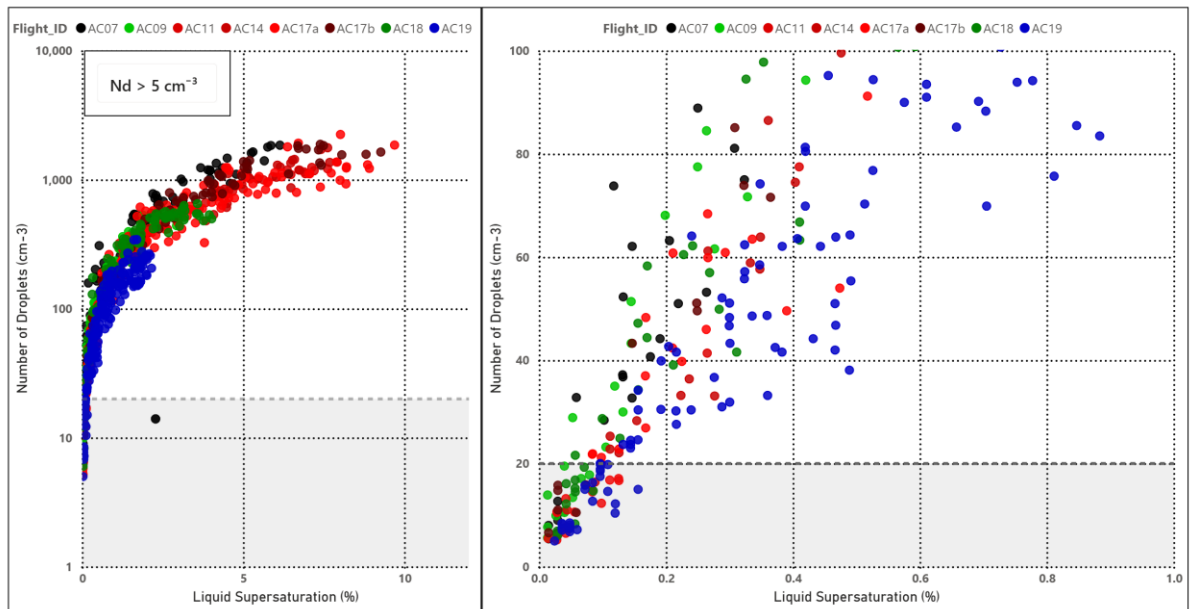


Figure R5. [left] Liquid Supersaturation (S_l) versus N_d for all flight segments ($N_d > 5 \text{ cm}^{-3}$). [right] Similar for ($N_d < 100 \text{ cm}^{-3}$ & $S_l < 1 \%$).

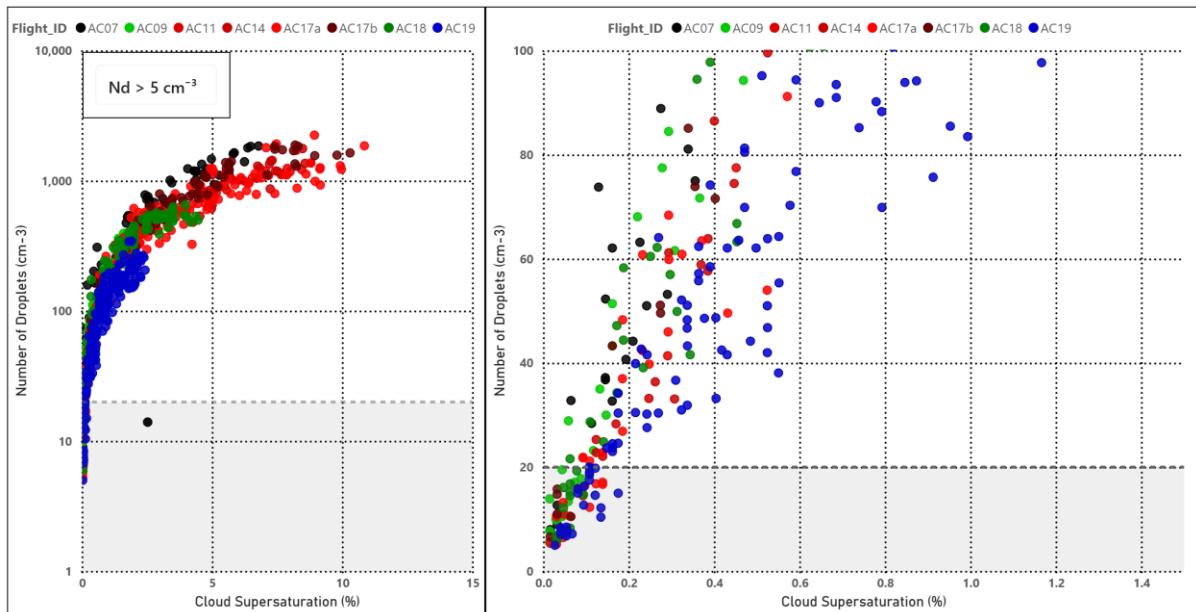


Figure R6. [left] Cloud Supersaturation (S_c) vs. N_d for all flight segments ($N_d > 5 \text{ cm}^{-3}$). [right] Similar for ($N_d < 100 \text{ cm}^{-3}$ & $S_c < 1.5 \%$).

3. The derived correlation coefficients values exhibit inverse correlation with the sample size. Larger sample sizes are associated with lower correlation coefficients and vice versa. Given the extremely limited sample size for this analysis and considering the prior argument, justify whether N_d is well constrained by S_v (Lines 408-409).

A: We agree with the referee that the correlation coefficients are sensitive to sample size and that larger datasets may produce lower R^2 values due to the inclusion of a broader range of atmospheric variability. In our observations, larger samples encompass more heterogeneous conditions in updraft velocity, turbulence intensity, and CCN concentrations, which increases scatter in the N_d - S_v relationship without necessarily invalidating the underlying physical dependence.

We also acknowledge that the present analysis is based on a limited number of cloud-base penetrations from the ACRIDICON-CHUVA campaign. Additional measurements covering a wider range of cloud regimes and environmental conditions would therefore be valuable in future studies to further evaluate the robustness and universality of the fitted power-law parameters.

At the same time, several independent results support the physical consistency of the proposed relationship. The fitted parameters C and k remain relatively stable across the sensitivity tests and threshold selections. More importantly, the N_d (S_v) spectra derived at cloud base agree, within the estimated uncertainties, with the independently measured CCN(S_v) spectra below cloud base (as described in the reply for referee #1).

We have revised the manuscript to clarify these limitations and to avoid overstating the statistical strength of the relationship. The results should therefore be interpreted as evidence supporting the proposed energetic framework and its consistency with cloud base observations, while recognizing that additional datasets are needed to further strengthen the statistical robustness of the derived power-law relationships.

We discuss the relevant statistical analysis in the new version of the manuscript at section 3.2 as follows:

“Figure 5 shows the droplet number spectra as a function of cloud supersaturations (S_c , S_l , S_v), $N_d(S)$, derived from cloud base measurements for all flight segments (see Tables 3-5 for the statistics of the fit parameters). The $N_d(S)$ were derived using power-law fits of the form $N_d = C \cdot S^k$, where C is a scaling factor and k is the spectral exponent. Across all three supersaturations derived larger values of C and k parameters are estimated for aerosol-rich conditions (e.g., AC07), whereas smaller k -values (e.g., AC19) reflect more CCN-limited regimes. The values of C and k have closer values for the power-law fits of N_d-S_c and N_d-S_l due to the similar values of Q and ΔU in the energetic budget partition ($\Delta U \sim 0.9 \cdot Q$). The high coefficients of determination ($R^2 > 0.87$) and low root-mean-square errors ($RMSE < 0.3$) indicate robust agreement between the fitted relationships and the observations under different atmospheric conditions. The tables show that the values of R^2 are sensitive to sample size, and larger cloud base datasets typically result in lower R^2 values due to the inclusion of a broader range of atmospheric variability. In our observations, larger samples encompass more heterogeneous conditions in updraft velocity, turbulence intensity, and CCN concentrations, which increase scatter in the N_d-S relationships. Nevertheless, the fitted parameters C and k remain relatively stable across the different environmental conditions owing to the underlying physical dependence between N_d and S . A more detailed description of this analysis accounting for different cloud detection thresholds and measurements uncertainties is provided in Section S2.3 of the Supplementary Material.”

4. The reported uncertainties of 10% for N and LWC at lines 307-309 are applicable only to the ACRIDICON-CHUVA dataset. These uncertainties can be considered as the best-case scenario for measurement uncertainties, given that the Baumgardner et al., 2017 report the uncertainty range for scattering probes for sizing to be 10%-50% and for concentrations to be 10%-30%. Therefore, to extend the energy balance method to be applicable for other datasets from other field campaigns and to account for the worst-case scenario containing the maximum possible range of energy terms and supersaturations, please consider discussing the uncertainty to be defined as both the best-case and worst-case scenarios.

A: In the reply for referee #1 we described the measurement uncertainties calculations applied for the data set. We wrote the following about that:

“Uncertainties in the meteorological measurements from the BAHAMAS system translate into an estimated average uncertainty of about 0.24% (typically $< 1\%$ for 1 Hz data) in the derived RH_c when calculating using the Bolton equation. The relative uncertainties of the energy terms were about 10% for Q and ΔU , and 13% for W_s . Propagating these errors yields overall uncertainties of $\sim 10\%$ for S_c and S_l , and $\sim 12\%$ for S_v .”

The uncertainties of energy terms and supersaturations are mostly sensitive to the LWC uncertainties. Baumgardner et al., (2017) report that the expected range of uncertainties in LWC and N_d is between 10% - 30%. For LWC uncertainty of 30%, the relative uncertainties of the energy terms are about 29% for Q and ΔU , and 38% for W_s . Propagating these errors yields overall uncertainties of $\sim 28\%$ for S_c and S_l , and $\sim 36\%$ for S_v . The figures below show the average values of these uncertainties for each flight, assuming LWC uncertainties of 10% and 30%.

Higher measurement uncertainties increase the scatter in the power-law relationship N_d-S relationship (shown in Tables S4-S6), as reflected by generally lower R^2 and similar or slightly higher RMSE values. However, the impact is not limited to statistical dispersion. The results show a systematic decrease in both C and k when uncertainties increase, indicating that uncertainty propagation affects not only the precision but also the magnitude of the fitted parameters. Despite these shifts, the power-law relationship remains consistent across thresholds and flights, and the variations in C and k are within the broader uncertainty range of the estimates. This indicates that while increased uncertainties reduce the strength of the

statistical fit and slightly bias the parameter values, they do not alter the underlying physical dependence of N_d on S_v .

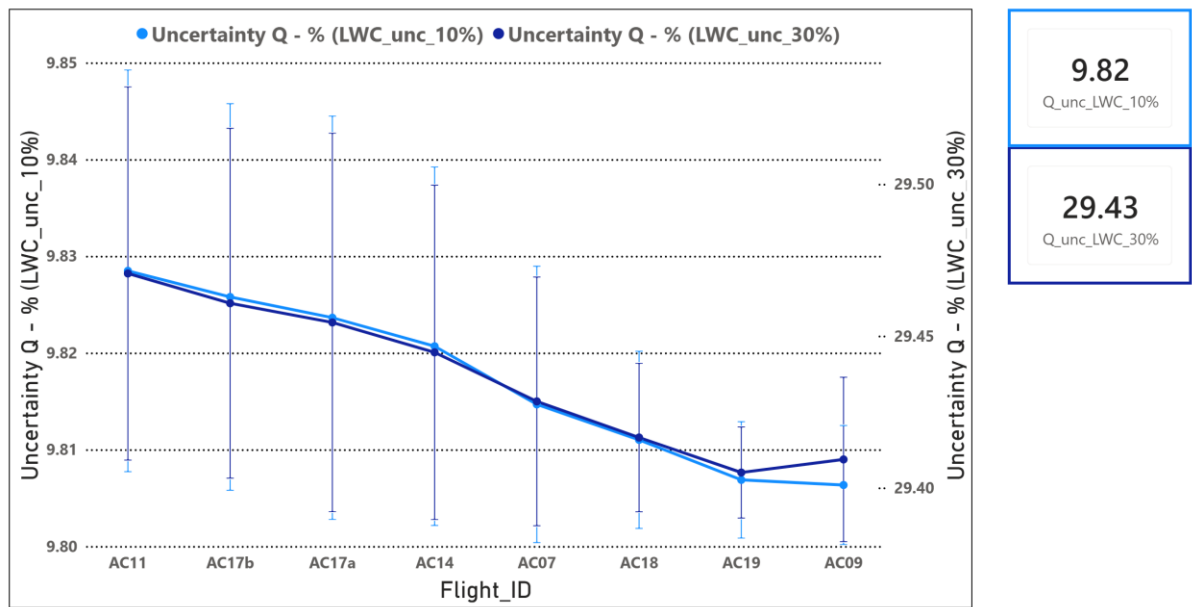


Figure R7. Relative uncertainty (%) of the latent heat term Q for each flight segment, derived from propagated liquid water content (LWC) uncertainties of 10% and 30%. Markers indicate flight-mean values and error bars represent $\pm 1\sigma$ variability within each segment. The right panel shows the mean uncertainty across all flights, highlighting the strong sensitivity of Q to LWC uncertainty.

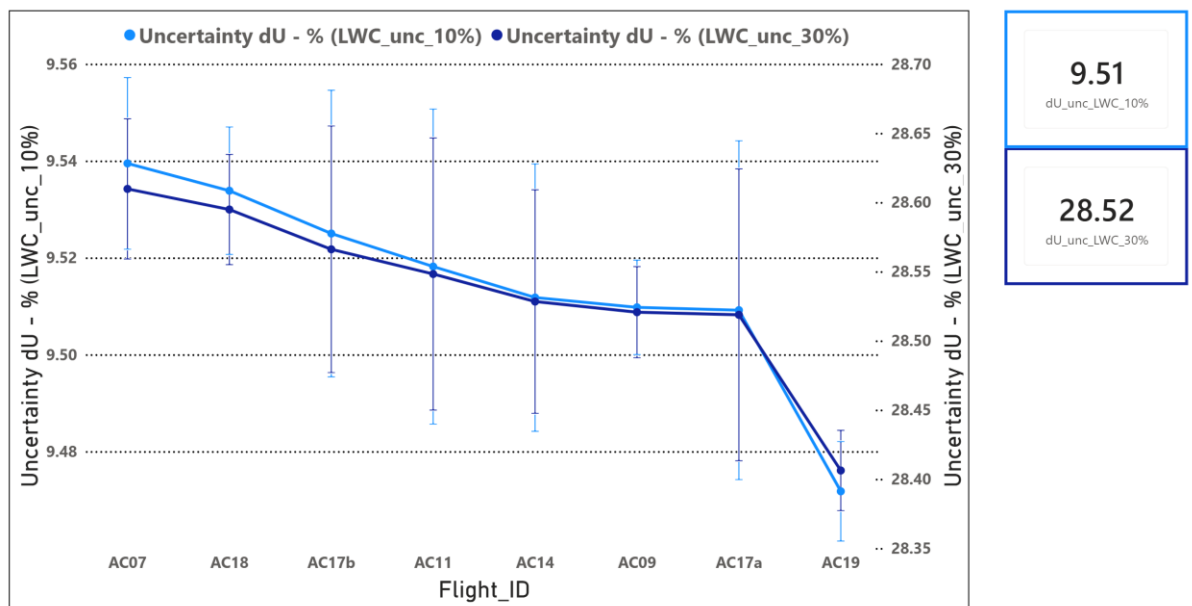


Figure R8. Similar to Figure R7 for the internal energy change ΔU for each flight segment. The right panel summarizes the mean uncertainty across all flights, showing similar sensitivity to LWC as observed for Q.

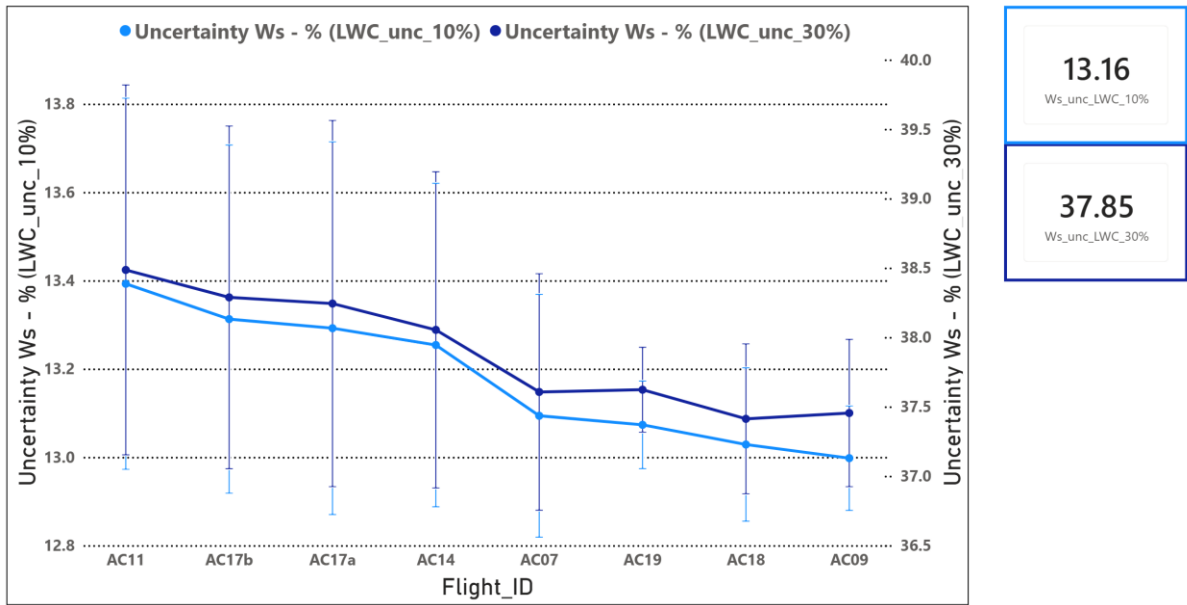


Figure R9. Similar to Figure R7 for the saturation work term W_s for each flight segment. The right panel indicates the mean uncertainty across flights, with larger sensitivity compared to Q and ΔU .

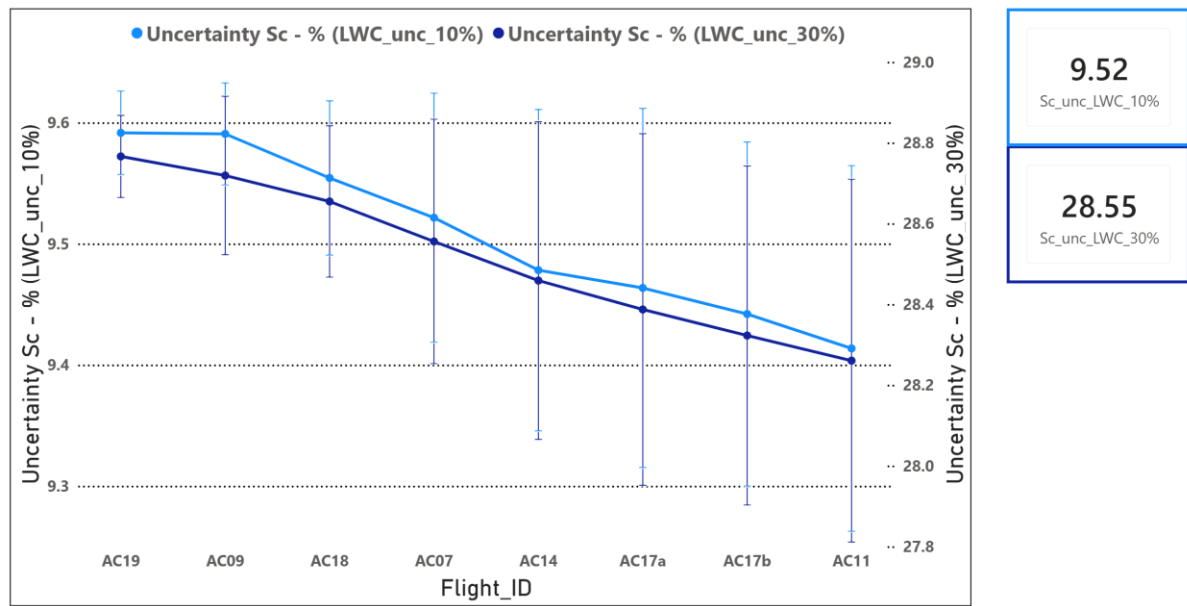


Figure R10. Similar to figure R7 for cloud supersaturation S_c for each flight segment. The right panel presents the mean uncertainty across all flights.

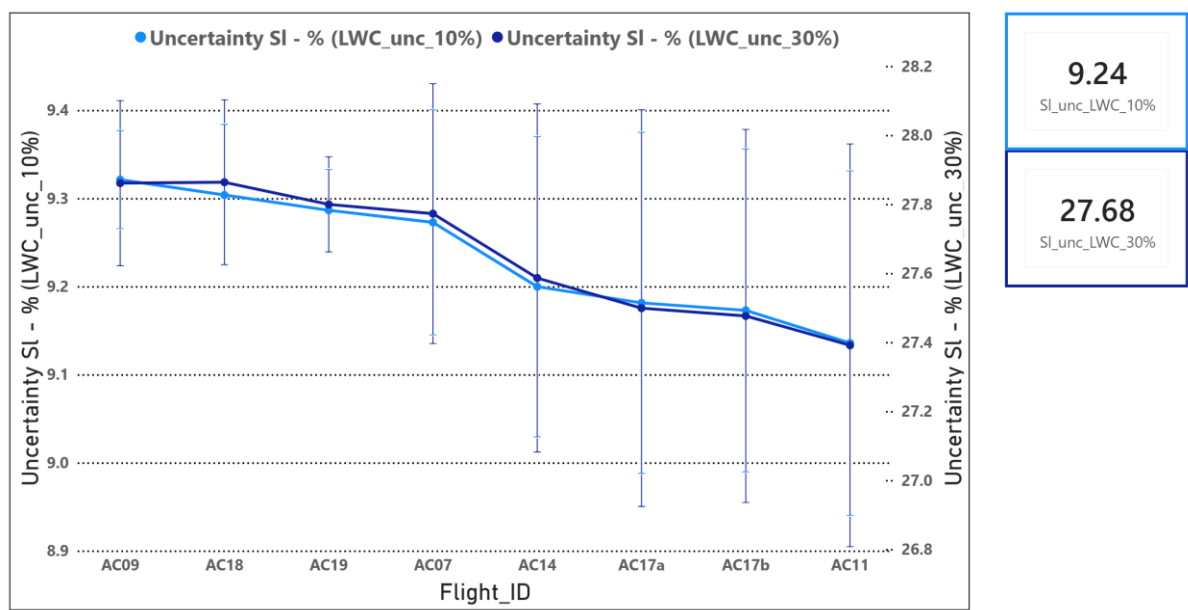


Figure R11. Similar to figure R7 for liquid supersaturation S_l for each flight segment. The right panel presents the mean uncertainty across all flights.

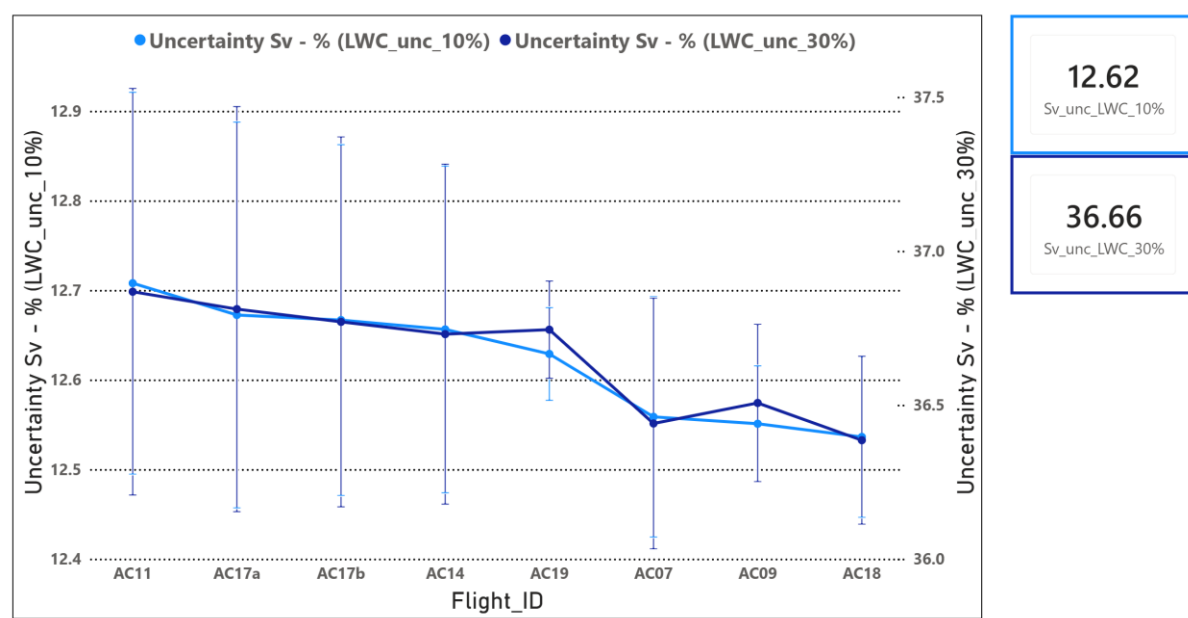


Figure R12. Similar to figure R7 for water vapor supersaturation S_v for each flight segment. The right panel summarizes the mean uncertainty across all flights, indicating higher sensitivity compared to S_c and S_l .

We discuss the effect of measurements uncertainties in the new version of the manuscript at section 2.7.3 and supplementary material as follows:

“The measurement uncertainties of the energy budget parameters were calculated using a Monte Carlo method (JCGM, 2008) and are described in Section 2.2 in the Supplementary Material. The uncertainties in the meteorological measurements from the BAHAMAS system translate into an estimated average uncertainty of about 0.24% (typically < 1% for 1 Hz data) in the derived RH_c. The relative uncertainties of the energy terms are about 10% for Q and ΔU , and 13% for W_s . Propagating these errors yields overall uncertainties of ~10% for S_c and S_l , and ~12% for S_v . The uncertainties of energy terms and supersaturations are mostly sensitive to the LWC uncertainties. Baumgardner et al. (2017) reports that expected range of uncertainties in LWC and N_d is between 10% and 30%. For LWC uncertainty of 30%, the relative uncertainties of the energy terms are about 29% for Q and ΔU , and 38% for W_s . Propagating these errors yields overall uncertainties of ~28% for S_c and S_l , and ~36% for S_v . These calculations are presented in Section S2.2 of the Supplementary Material.

The uncertainties of the power-law relationship $N_d = C \cdot S_v^k$ fitted for each flight segment shown in this manuscript were also calculated using Monte Carlo uncertainty propagation (using 10% for N_d and 12.6% for S_v). These calculations are presented in Section S2.3 of the Supplementary Material. Across all flights, the exponent is well constrained with uncertainties of $\sigma k \approx 0.01$ –0.03, while the C shows relative uncertainties of approximately 2–6%. Higher measurement uncertainties increase the scatter in the power-law relationship N_d - S_v relationships (shown in Tables S4-S6). Our analysis show a systematic decrease in both C and k when uncertainties increase, indicating that uncertainty propagation affects not only the precision but also the magnitude of the fitted parameters. Despite these shifts, the power-law relationship remains consistent across thresholds and flights, and the variations in C and k are within the broader uncertainty range of the estimates. This indicates that while increased uncertainties reduce the strength of the statistical fit and slightly bias the parameter values, they do not alter the underlying physical dependence of N_d on S_c , S_l , and S_v .”

5. Lines 473-474: Please provide the magnitude of overestimation to better highlight the importance of including the energetic cost of vapor expansion during the ascent of the saturated parcel.

A: The figures below quantify the energetic cost of vapor expansion work (W_s) on liquid water content (LWC) estimates at cloud base as a function of adiabatic cooling (ΔT) and initial temperature (T_0) for pressures of 950 hPa and 850 hPa. The inclusion of W_s reduces the LWC by a factor that depends primarily on T_0 and only weakly on ΔT .

At 950 hPa, the fractional reduction in LWC ranges from approximately 4-6% at low temperatures ($\sim 2-6^\circ\text{C}$) to 16-20% at higher temperatures ($\sim 25-30^\circ\text{C}$). At 850 hPa, the reduction is slightly larger, increasing from $\sim 5-7\%$ to $\sim 18-22\%$ over the same temperature ranges.

At lower pressure, the volumetric LWC is reduced because the dry-air density decreases. At fixed ΔT and T_0 , the lower pressure case has a larger saturation mixing ratio (r_s), since it increases as $p - e_s(T_0)$ decreases (see equations below). Therefore, W_s is slightly higher at 850 hPa than at 950 hPa. These factors lead to a larger fractional reduction in LWC when W_s is included.

LWC derivation for the ascending saturated parcel according to the energetic partition:

$$\Delta U = Q - W_s \quad (1)$$

$$LWC = \rho_{air} \cdot \frac{\Delta U}{L_v} \quad (2)$$

where:

$$Q = |\Delta H| \quad \therefore \quad L_v \cdot q_l = |-c_{p,cloud} \cdot \Delta T| = c_{p,cloud} \cdot (T_0 - T) \quad (3)$$

$$q_l = LWC / \rho_{air} \quad (4)$$

$$\rho_{air} = \frac{p - e_s(T_0)}{R_d \cdot T_0} \quad (5)$$

$$W_s = r_{s0} \cdot R_v \cdot T_0 \cdot \ln\left(\frac{\alpha_{vs}}{\alpha_{vs0}}\right) \quad (6)$$

$$r_{s0} = (R_d/R_v) \cdot \frac{e_s(T_0)}{p - e_s(T_0)} \quad (7)$$

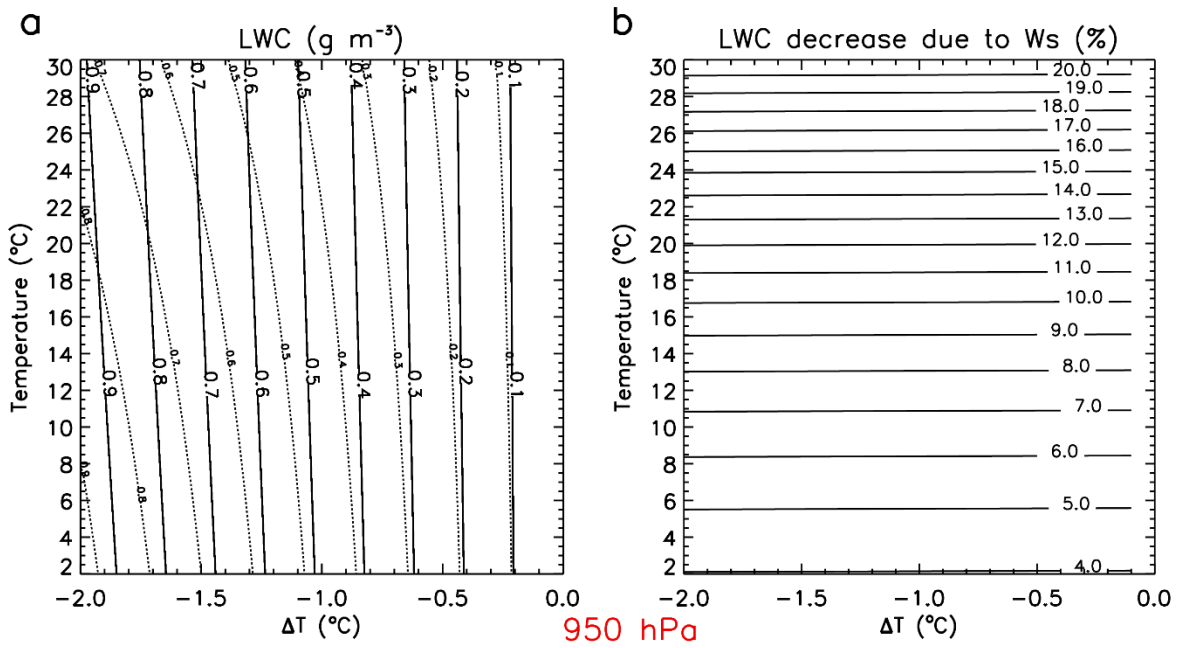


Figure R13. Liquid water content (LWC) and its reduction due to vapor expansion work (W_s) at cloud base for a pressure of 950 hPa, shown as a function of cooling (ΔT) and initial temperature (T_0). (a) LWC (g m^{-3}) calculated assuming all the enthalpy change ($Q = dH$) contributes to condensational growth of particles (solid contours), with the corresponding LWC including the effect of W_s shown as dotted contours. (b) Fractional decrease in LWC (%) due to the inclusion of W_s .

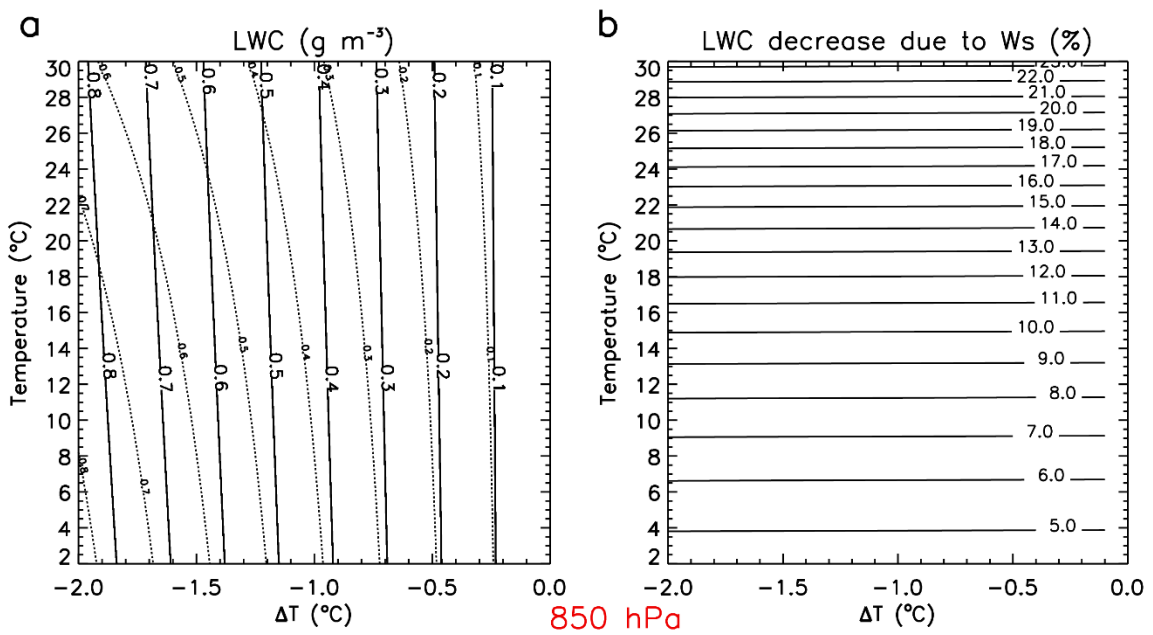


Figure R14. Similar to Figure R13 for 850 hPa.

We discuss the importance of including the energetic cost of vapor expansion during the ascent of the saturated parcel at the new section 3.1 as follows:

“To illustrate the thermodynamic basis of the energetic budget analysis at cloud base, we first describe the fundamental relationships between the initial temperature of the saturated parcel (T_0) and adiabatic cooling ΔT resulting from the ascent for T_0 ranging from 2°C to 30°C. Figure 2 shows the simulated values of LWC, Q , ΔU , and W_s resulting from the energy balance at a pressure level of 950 hPa. All quantities from the energy balance are expressed as positive values to represent the partition of the total energy (Q) during the condensational growth. In the case in which water vapor is fully condensed ($Q = dH$) the LWC (solid lines) increase almost linearly with cooling rate for different T_0 . For the same cooling rate, a slightly larger LWC is calculated for lower temperatures owing to the higher dry air density of the saturated parcel. ***When accounting for W_s in the energy budget, the resulting values of LWC (dotted lines) are relatively smaller. At 950 hPa, the fractional reduction in LWC due to W_s increases approximately linearly with temperature, ranging from about 4-6% at low temperatures ($\sim 2-6$ °C) to 15-20% at higher temperatures ($\sim 25-30$ °C) (see Figure S1).*** The values of ΔU are slightly smaller than Q since the total energy is partitioned with W_s , which increases approximately linearly with temperature and logarithmically with the cooling rate.

Figure 3 shows the corresponding values of RH_c , S_c , S_l , and S_v derived from the energy budget framework. Figures 3a-b show RH_c decreasing below 100%, with a corresponding increase of S_c above 0% as a function of the prescribed adiabatic cooling. For a given cooling magnitude, the increase in S_c becomes slightly smaller at warmer temperatures because the fractional reduction in RH_c [$e_s(T)/e_s(T_0)$] for a fixed ΔT decreases slightly with increasing T_0 , consistent with the temperature dependence of the Clausius-Clapeyron relation. Figures 3c-d show the partitioning of S_c into S_l and S_v resulting from the energy budget analysis. The values of S_l are about one order of magnitude larger than S_v , indicating that most of the enthalpy change associated with adiabatic cooling and condensation contributes to vapor-to-liquid conversion and condensational growth, while W_s represents a smaller fraction of the total energy budget. Since W_s increases with T_0 , S_v becomes relatively larger under warmer cloud-base conditions for the same cooling magnitude, whereas the opposite behaviour is observed for S_l . This emphasizes the increasing contribution of saturation work to the total energy budget at warmer temperatures, which enhances S_v while reducing the fraction of energy available for condensational growth of cloud particles.

These relationships between energetic partitioning and the vapor budget remain qualitatively similar under lower-pressure conditions. However, as pressure decreases, the LWC is reduced because the density of dry air decreases. Furthermore, for a given T_0 and ΔT , the magnitude of W_s is slightly enhanced at lower pressures due to the larger saturation mixing ratio (see Eq. 5), thereby increasing the contribution of water vapor expansion to the total energy budget. Consequently, a smaller fraction of the enthalpy change associated with cooling and condensation contributes to vapor-to-liquid conversion and condensational growth. ***At 850 hPa, for example, the reduction in LWC associated with W_s ranges from approximately 5-7% at low temperatures ($\sim 2-6$ °C) to about 18-22% at higher temperatures ($\sim 25-30$ °C) (Figure S2).*** The larger contribution of W_s to the energy budget leads to slightly larger S_v and smaller S_l relatively to those at 950 hPa.”

Technical corrections:

1. The spelling of 'modeling' in the manuscript is inconsistent. At Lines 33,36,237, it is spelled as 'modeling', whereas at lines 189, 226, 467 it is spelled as 'modelling'.

A: Ok. Thanks.

2. Figure 3 and 4: Include a description in the figure captions that indicates that the color choices correspond to different aerosol backgrounds in the Amazon region and list the colors with their corresponding regions.

A: Ok. Thanks for this suggestion.

We added that in the new Figure 5.

Reference:

Baumgardner, D., and Coauthors, 2017: Cloud Ice Properties: In Situ Measurement Challenges. Meteor. Monogr., 58, 9.1–9.23, <https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0011.1>

Citation: <https://doi.org/10.5194/egusphere-2026-795-RC2>

Supporting Information: Sensitivity of the N_d - S relationship to prescribed uncertainties

To quantify the impact of measurement and retrieval uncertainties on the fitted relationship between droplet number concentration and supersaturation, we performed a Monte Carlo uncertainty analysis of the power-law relation:

$$N_d = C \cdot S^k$$

The regression was conducted in log-log space. Uncertainties in both variables were propagated by perturbing the observed values of S (S_c , S_l , and S_v) and N_d assuming Gaussian-distributed errors.

Two uncertainty scenarios were considered for each N_d and S values based on the average uncertainties:

- Best-case scenario: 12.6 % uncertainty in S_v , 9.2 % uncertainty in S_l , 9.5 % uncertainty in S_c , and 10% in N_d .
- Worst-case scenario: 36.6 % uncertainty in S_v , 27.6 % uncertainty in S_l , 28.5 % uncertainty in S_c , and 30% in N_d .

For each case, 5000 Monte Carlo realizations were performed, and the mean and standard deviation of the fitted parameters were calculated (JCGM, 2008).

The conversion of N_d to Standard Temperature and Pressure (STP; $p = 1013.25$ hPa and $T = 273.15$ K) when comparing with CCN(S_v) spectra measured below cloud bases introduces negligible additional uncertainty relative to the instrumental uncertainty in N_d . For typical cloud base conditions, a temperature uncertainty of 0.5 K contributes approximately 0.17%, while a pressure uncertainty of 3 Pa contributes less than 0.01%. Therefore, the total relative uncertainty in $N_{d\text{STP}}$ remains dominated by the assumed 10% uncertainty in N_d .

This information can be found in Section S2.3 in the revised supplementary material.

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Khain, A. P. and Pinsky, M.: Physical Processes in Clouds and Cloud Modeling, <https://doi.org/10.1017/9781139049481>, 2018.

Twomey, S.: The nuclei of natural cloud formation part II: The supersaturation in natural clouds and the variation of cloud droplet concentration, *Geofisica Pura e Applicata*, 43, 243–249, <https://doi.org/10.1007/BF01993560>, 1959.

Table S1. Power-law fit parameters for the relationship $N_d = C \cdot S_v^k$ derived from log–log regression. The coefficients C and k are reported as Monte Carlo means $\pm 1\sigma$ ($n = 5000$ realizations). The coefficient of determination (R^2) and root-mean-square error (RMSE) are calculated from the nominal fit in logarithmic space. Data are filtered using threshold criteria $N_d > N_{d,th}$ and $LWC > LWC_{th}$. The uncertainties of N_d and S_v assumed in the calculations are 10% and 12.6%, respectively. Columns list: Flight ID, $N_{d,th}$, LWC_{th} , C , σC , k , σk , R^2 , RMSE, and sample size (N).

Flight	$N_{d,th}$	LWC_{th}	C	σC	k	σk	R^2	RMSE	N
AC07	10	0	2017.67	66.2	0.883	0.013	0.783	0.645	81
AC07	10	0.01	2068.73	82.01	0.899	0.02	0.657	0.678	71
AC07	10	0.02	2062.85	100.38	0.896	0.028	0.533	0.698	64
AC07	20	0	2414.84	82.16	0.922	0.014	0.958	0.249	77
AC07	20	0.01	2478.51	92.39	0.939	0.018	0.947	0.234	69
AC07	20	0.02	2441.89	102.81	0.926	0.024	0.943	0.193	62
AC07	30	0	2396.08	82.23	0.917	0.014	0.956	0.25	76
AC07	30	0.01	2478.51	92.39	0.939	0.018	0.947	0.234	69
AC07	30	0.02	2441.89	102.81	0.926	0.024	0.943	0.193	62
AC09	10	0	1347.58	67.91	0.832	0.015	0.956	0.244	48
AC09	10	0.01	1306.68	96.08	0.808	0.029	0.941	0.169	37
AC09	10	0.02	1406.77	132.03	0.845	0.042	0.91	0.173	32
AC09	20	0	1349.85	85.34	0.826	0.023	0.952	0.19	41
AC09	20	0.01	1306.68	96.08	0.808	0.029	0.941	0.169	37
AC09	20	0.02	1406.77	132.03	0.845	0.042	0.91	0.173	32
AC09	30	0	1326.86	93.99	0.815	0.028	0.949	0.167	38
AC09	30	0.01	1306.68	96.08	0.808	0.029	0.941	0.169	37
AC09	30	0.02	1406.77	132.03	0.845	0.042	0.91	0.173	32
AC11	10	0	1575.37	61.52	0.931	0.02	0.99	0.125	35
AC11	10	0.01	1565.84	67.87	0.924	0.028	0.982	0.125	33
AC11	10	0.02	1535.06	66.03	0.9	0.03	0.98	0.118	32
AC11	20	0	1565.84	67.87	0.924	0.028	0.982	0.125	33
AC11	20	0.01	1565.84	67.87	0.924	0.028	0.982	0.125	33
AC11	20	0.02	1535.06	66.03	0.9	0.03	0.98	0.118	32
AC11	30	0	1565.84	67.87	0.924	0.028	0.982	0.125	33

AC11	30	0.01	1565.84	67.87	0.924	0.028	0.982	0.125	33
AC11	30	0.02	1535.06	66.03	0.9	0.03	0.98	0.118	32
AC14	10	0	1595.69	49.67	0.951	0.015	0.979	0.18	74
AC14	10	0.01	1651.26	55.23	0.978	0.018	0.977	0.166	70
AC14	10	0.02	1604.71	54.92	0.948	0.02	0.972	0.153	65
AC14	20	0	1643.14	52.98	0.973	0.016	0.981	0.164	73
AC14	20	0.01	1651.26	55.23	0.978	0.018	0.977	0.166	70
AC14	20	0.02	1604.71	54.92	0.948	0.02	0.972	0.153	65
AC14	30	0	1650.02	54.81	0.977	0.019	0.975	0.167	69
AC14	30	0.01	1650.02	54.81	0.977	0.019	0.975	0.167	69
AC14	30	0.02	1604.71	54.92	0.948	0.02	0.972	0.153	65
AC17a	10	0	1501.55	31.98	0.928	0.009	0.961	0.271	131
AC17a	10	0.01	1460.03	34.89	0.899	0.013	0.934	0.263	117
AC17a	10	0.02	1449.64	37.55	0.891	0.017	0.9	0.267	108
AC17a	20	0	1465.85	34.06	0.903	0.012	0.947	0.26	121
AC17a	20	0.01	1460.03	34.89	0.899	0.013	0.934	0.263	117
AC17a	20	0.02	1449.64	37.55	0.891	0.017	0.9	0.267	108
AC17a	30	0	1449.85	35.18	0.892	0.014	0.931	0.263	116
AC17a	30	0.01	1449.85	35.18	0.892	0.014	0.931	0.263	116
AC17a	30	0.02	1449.64	37.55	0.891	0.017	0.9	0.267	108
AC17b	10	0	1893.74	53.69	0.916	0.013	0.978	0.201	69
AC17b	10	0.01	2002.72	67.55	0.963	0.02	0.973	0.159	63
AC17b	10	0.02	1978.54	68.29	0.95	0.023	0.967	0.16	61
AC17b	20	0	1983.55	64.99	0.954	0.019	0.975	0.161	64
AC17b	20	0.01	2002.72	67.55	0.963	0.02	0.973	0.159	63
AC17b	20	0.02	1978.54	68.29	0.95	0.023	0.967	0.16	61
AC17b	30	0	1983.55	64.99	0.954	0.019	0.975	0.161	64
AC17b	30	0.01	2002.72	67.55	0.963	0.02	0.973	0.159	63
AC17b	30	0.02	1978.54	68.29	0.95	0.023	0.967	0.16	61
AC18	10	0	1470.38	45.75	0.866	0.012	0.961	0.214	106

AC18	10	0.01	1405.33	53.13	0.84	0.017	0.927	0.212	96
AC18	10	0.02	1321.65	58.49	0.8	0.022	0.881	0.211	87
AC18	20	0	1417.28	51.16	0.845	0.016	0.94	0.213	99
AC18	20	0.01	1405.33	53.13	0.84	0.017	0.927	0.212	96
AC18	20	0.02	1321.65	58.49	0.8	0.022	0.881	0.211	87
AC18	30	0	1405.33	53.13	0.84	0.017	0.927	0.212	96
AC18	30	0.01	1405.33	53.13	0.84	0.017	0.927	0.212	96
AC18	30	0.02	1321.65	58.49	0.8	0.022	0.881	0.211	87
AC19	10	0	790.19	25.96	0.855	0.012	0.912	0.247	177
AC19	10	0.01	756.29	28.46	0.833	0.015	0.875	0.244	164
AC19	10	0.02	725.67	33.31	0.811	0.02	0.817	0.243	148
AC19	20	0	740.31	27.76	0.822	0.015	0.874	0.24	163
AC19	20	0.01	740.31	27.76	0.822	0.015	0.874	0.24	163
AC19	20	0.02	725.67	33.31	0.811	0.02	0.817	0.243	148
AC19	30	0	714.42	29.42	0.804	0.017	0.847	0.243	157
AC19	30	0.01	714.42	29.42	0.804	0.017	0.847	0.243	157
AC19	30	0.02	725.67	33.31	0.811	0.02	0.817	0.243	148

Table S2. Power-law fit parameters for the relationship $N_d = C \cdot S_l^k$ derived from log–log regression. The coefficients C and k are reported as Monte Carlo means $\pm 1\sigma$ ($n = 5000$ realizations). The coefficient of determination (R^2) and root-mean-square error (RMSE) are calculated from the nominal fit in logarithmic space. Data are filtered using threshold criteria $N_d > N_{d,th}$ and $LWC > LWC_{th}$. The uncertainties of N_d and S_l assumed in the calculations are 10% and 9.2%, respectively. Columns list: Flight ID, $N_{d,th}$, LWC_{th} , C , σC , k , σk , R^2 , RMSE, and sample size (N).

Flight	$N_{d,th}$	LWC_{th}	C	σC	k	σk	R^2	RMSE	N
AC07	10	0	268.66	4	0.895	0.011	0.788	0.638	81
AC07	10	0.01	263.48	4.7	0.919	0.017	0.664	0.671	71
AC07	10	0.02	262.04	6.19	0.926	0.024	0.543	0.691	64
AC07	20	0	293.63	4.51	0.932	0.012	0.958	0.249	77
AC07	20	0.01	288.53	5.22	0.954	0.016	0.948	0.233	69
AC07	20	0.02	290.75	6.53	0.948	0.021	0.942	0.194	62
AC07	30	0	294.76	4.63	0.927	0.012	0.956	0.249	76
AC07	30	0.01	288.53	5.22	0.954	0.016	0.948	0.233	69
AC07	30	0.02	290.75	6.53	0.948	0.021	0.942	0.194	62
AC09	10	0	221.36	4.72	0.838	0.013	0.957	0.243	48
AC09	10	0.01	225.78	4.88	0.821	0.026	0.944	0.166	37
AC09	10	0.02	223.16	5.14	0.866	0.037	0.913	0.169	32
AC09	20	0	224.22	4.88	0.836	0.02	0.953	0.188	41
AC09	20	0.01	225.78	4.88	0.821	0.026	0.944	0.166	37
AC09	20	0.02	223.16	5.14	0.866	0.037	0.913	0.169	32
AC09	30	0	225.51	4.88	0.829	0.024	0.951	0.164	38
AC09	30	0.01	225.78	4.88	0.821	0.026	0.944	0.166	37
AC09	30	0.02	223.16	5.14	0.866	0.037	0.913	0.169	32
AC11	10	0	187.75	5.06	0.953	0.017	0.99	0.121	35
AC11	10	0.01	186.53	6.54	0.959	0.025	0.983	0.12	33
AC11	10	0.02	192.65	7.45	0.936	0.027	0.981	0.114	32
AC11	20	0	186.53	6.54	0.959	0.025	0.983	0.12	33
AC11	20	0.01	186.53	6.54	0.959	0.025	0.983	0.12	33
AC11	20	0.02	192.65	7.45	0.936	0.027	0.981	0.114	32
AC11	30	0	186.53	6.54	0.959	0.025	0.983	0.12	33

AC11	30	0.01	186.53	6.54	0.959	0.025	0.983	0.12	33
AC11	30	0.02	192.65	7.45	0.936	0.027	0.981	0.114	32
AC14	10	0	190.43	3.25	0.969	0.013	0.981	0.173	74
AC14	10	0.01	185.13	3.59	1	0.015	0.979	0.157	70
AC14	10	0.02	190.9	4.37	0.975	0.018	0.974	0.147	65
AC14	20	0	186.46	3.33	0.993	0.014	0.983	0.157	73
AC14	20	0.01	185.13	3.59	1	0.015	0.979	0.157	70
AC14	20	0.02	190.9	4.37	0.975	0.018	0.974	0.147	65
AC14	30	0	185.14	3.78	1	0.016	0.977	0.158	69
AC14	30	0.01	185.14	3.78	1	0.016	0.977	0.158	69
AC14	30	0.02	190.9	4.37	0.975	0.018	0.974	0.147	65
AC17a	10	0	188.32	2.3	0.948	0.008	0.964	0.261	131
AC17a	10	0.01	193.17	2.94	0.929	0.012	0.938	0.254	117
AC17a	10	0.02	192.78	3.79	0.931	0.015	0.907	0.258	108
AC17a	20	0	193.22	2.72	0.928	0.01	0.951	0.251	121
AC17a	20	0.01	193.17	2.94	0.929	0.012	0.938	0.254	117
AC17a	20	0.02	192.78	3.79	0.931	0.015	0.907	0.258	108
AC17a	30	0	194.63	2.99	0.923	0.012	0.935	0.254	116
AC17a	30	0.01	194.63	2.99	0.923	0.012	0.935	0.254	116
AC17a	30	0.02	192.78	3.79	0.931	0.015	0.907	0.258	108
AC17b	10	0	234.08	4.08	0.931	0.011	0.979	0.195	69
AC17b	10	0.01	218.89	5.28	0.991	0.018	0.976	0.15	63
AC17b	10	0.02	221.56	5.91	0.982	0.02	0.97	0.151	61
AC17b	20	0	222.25	5.02	0.979	0.017	0.977	0.153	64
AC17b	20	0.01	218.89	5.28	0.991	0.018	0.976	0.15	63
AC17b	20	0.02	221.56	5.91	0.982	0.02	0.97	0.151	61
AC17b	30	0	222.25	5.02	0.979	0.017	0.977	0.153	64
AC17b	30	0.01	218.89	5.28	0.991	0.018	0.976	0.15	63
AC17b	30	0.02	221.56	5.91	0.982	0.02	0.97	0.151	61
AC18	10	0	208.28	2.6	0.878	0.01	0.962	0.21	106

AC18	10	0.01	210.65	2.84	0.858	0.015	0.93	0.208	96
AC18	10	0.02	215.24	3.39	0.826	0.02	0.885	0.207	87
AC18	20	0	210.1	2.8	0.861	0.014	0.942	0.209	99
AC18	20	0.01	210.65	2.84	0.858	0.015	0.93	0.208	96
AC18	20	0.02	215.24	3.39	0.826	0.02	0.885	0.207	87
AC18	30	0	210.65	2.84	0.858	0.015	0.93	0.208	96
AC18	30	0.01	210.65	2.84	0.858	0.015	0.93	0.208	96
AC18	30	0.02	215.24	3.39	0.826	0.02	0.885	0.207	87
AC19	10	0	133.38	1.43	0.869	0.011	0.914	0.244	177
AC19	10	0.01	133.61	1.42	0.852	0.013	0.878	0.241	164
AC19	10	0.02	133.78	1.42	0.838	0.018	0.82	0.241	148
AC19	20	0	133.75	1.41	0.841	0.014	0.876	0.238	163
AC19	20	0.01	133.75	1.41	0.841	0.014	0.876	0.238	163
AC19	20	0.02	133.78	1.42	0.838	0.018	0.82	0.241	148
AC19	30	0	133.96	1.41	0.825	0.015	0.85	0.24	157
AC19	30	0.01	133.96	1.41	0.825	0.015	0.85	0.24	157
AC19	30	0.02	133.78	1.42	0.838	0.018	0.82	0.241	148

Table S3. Power-law fit parameters for the relationship $N_d = C \cdot S_c^k$ derived from log–log regression. The coefficients C and k are reported as Monte Carlo means $\pm 1\sigma$ ($n = 5000$ realizations). The coefficient of determination (R^2) and root-mean-square error (RMSE) are calculated from the nominal fit in logarithmic space. Data are filtered using threshold criteria $N_d > N_{d,th}$ and $LWC > LWC_{th}$. The uncertainties of N_d and S_c assumed in the calculations are 10% and 9.5%, respectively. Columns list: Flight ID, $N_{d,th}$, LWC_{th} , C , σC , k , σk , R^2 , RMSE, and sample size (N).

Flight	$N_{d,th}$	LWC_{th}	C	σC	k	σk	R^2	RMSE	N
AC07	10	0	246.3	3.76	0.894	0.011	0.787	0.639	81
AC07	10	0.01	241.14	4.56	0.917	0.017	0.663	0.672	71
AC07	10	0.02	239.92	6.17	0.923	0.024	0.542	0.691	64
AC07	20	0	268.24	4.25	0.931	0.012	0.958	0.249	77
AC07	20	0.01	263.13	5.02	0.953	0.016	0.948	0.233	69
AC07	20	0.02	265.5	6.41	0.946	0.021	0.942	0.194	62
AC07	30	0	269.41	4.36	0.926	0.012	0.956	0.249	76
AC07	30	0.01	263.13	5.02	0.953	0.016	0.948	0.233	69
AC07	30	0.02	265.5	6.41	0.946	0.021	0.942	0.194	62
AC09	10	0	202.17	4.23	0.837	0.013	0.957	0.243	48
AC09	10	0.01	206.62	4.42	0.82	0.026	0.943	0.166	37
AC09	10	0.02	203.28	4.86	0.865	0.038	0.913	0.17	32
AC09	20	0	204.84	4.36	0.835	0.02	0.953	0.188	41
AC09	20	0.01	206.62	4.42	0.82	0.026	0.943	0.166	37
AC09	20	0.02	203.28	4.86	0.865	0.038	0.913	0.17	32
AC09	30	0	206.21	4.39	0.827	0.025	0.951	0.164	38
AC09	30	0.01	206.62	4.42	0.82	0.026	0.943	0.166	37
AC09	30	0.02	203.28	4.86	0.865	0.038	0.913	0.17	32
AC11	10	0	171.16	4.84	0.951	0.018	0.99	0.121	35
AC11	10	0.01	170.26	6.36	0.955	0.025	0.983	0.12	33
AC11	10	0.02	176.3	7.27	0.933	0.027	0.981	0.114	32
AC11	20	0	170.26	6.36	0.955	0.025	0.983	0.12	33
AC11	20	0.01	170.26	6.36	0.955	0.025	0.983	0.12	33
AC11	20	0.02	176.3	7.27	0.933	0.027	0.981	0.114	32

AC11	30	0	170.26	6.36	0.955	0.025	0.983	0.12	33
AC11	30	0.01	170.26	6.36	0.955	0.025	0.983	0.12	33
AC11	30	0.02	176.3	7.27	0.933	0.027	0.981	0.114	32
AC14	10	0	172.53	3.07	0.968	0.013	0.981	0.174	74
AC14	10	0.01	167.28	3.45	0.998	0.016	0.979	0.158	70
AC14	10	0.02	173.05	4.23	0.972	0.018	0.974	0.147	65
AC14	20	0	168.55	3.17	0.991	0.014	0.983	0.157	73
AC14	20	0.01	167.28	3.45	0.998	0.016	0.979	0.158	70
AC14	20	0.02	173.05	4.23	0.972	0.018	0.974	0.147	65
AC14	30	0	167.31	3.64	0.997	0.016	0.977	0.159	69
AC14	30	0.01	167.31	3.64	0.997	0.016	0.977	0.159	69
AC14	30	0.02	173.05	4.23	0.972	0.018	0.974	0.147	65
AC17a	10	0	171.04	2.16	0.946	0.008	0.964	0.262	131
AC17a	10	0.01	176.01	2.85	0.926	0.012	0.938	0.255	117
AC17a	10	0.02	175.85	3.71	0.927	0.015	0.906	0.259	108
AC17a	20	0	175.97	2.61	0.926	0.011	0.95	0.252	121
AC17a	20	0.01	176.01	2.85	0.926	0.012	0.938	0.255	117
AC17a	20	0.02	175.85	3.71	0.927	0.015	0.906	0.259	108
AC17a	30	0	177.47	2.9	0.919	0.012	0.935	0.254	116
AC17a	30	0.01	177.47	2.9	0.919	0.012	0.935	0.254	116
AC17a	30	0.02	175.85	3.71	0.927	0.015	0.906	0.259	108
AC17b	10	0	213.86	3.88	0.929	0.011	0.979	0.196	69
AC17b	10	0.01	199.07	5.12	0.988	0.018	0.976	0.151	63
AC17b	10	0.02	201.81	5.76	0.979	0.02	0.97	0.152	61
AC17b	20	0	202.3	4.86	0.976	0.017	0.977	0.153	64
AC17b	20	0.01	199.07	5.12	0.988	0.018	0.976	0.151	63
AC17b	20	0.02	201.81	5.76	0.979	0.02	0.97	0.152	61
AC17b	30	0	202.3	4.86	0.976	0.017	0.977	0.153	64
AC17b	30	0.01	199.07	5.12	0.988	0.018	0.976	0.151	63
AC17b	30	0.02	201.81	5.76	0.979	0.02	0.97	0.152	61

AC18	10	0	190.81	2.4	0.877	0.01	0.962	0.21	106
AC18	10	0.01	193.45	2.72	0.857	0.015	0.929	0.209	96
AC18	10	0.02	198.4	3.37	0.824	0.02	0.885	0.208	87
AC18	20	0	192.87	2.65	0.859	0.014	0.942	0.209	99
AC18	20	0.01	193.45	2.72	0.857	0.015	0.929	0.209	96
AC18	20	0.02	198.4	3.37	0.824	0.02	0.885	0.208	87
AC18	30	0	193.45	2.72	0.857	0.015	0.929	0.209	96
AC18	30	0.01	193.45	2.72	0.857	0.015	0.929	0.209	96
AC18	30	0.02	198.4	3.37	0.824	0.02	0.885	0.208	87
AC19	10	0	120.43	1.24	0.868	0.011	0.914	0.245	177
AC19	10	0.01	120.91	1.24	0.85	0.014	0.878	0.242	164
AC19	10	0.02	121.27	1.28	0.835	0.018	0.82	0.241	148
AC19	20	0	121.18	1.24	0.839	0.014	0.876	0.238	163
AC19	20	0.01	121.18	1.24	0.839	0.014	0.876	0.238	163
AC19	20	0.02	121.27	1.28	0.835	0.018	0.82	0.241	148
AC19	30	0	121.6	1.26	0.823	0.016	0.85	0.241	157
AC19	30	0.01	121.6	1.26	0.823	0.016	0.85	0.241	157
AC19	30	0.02	121.27	1.28	0.835	0.018	0.82	0.241	148

Table S4. Power-law fit parameters for the relationship $N_d = C \cdot S_v^k$ derived from log–log regression. The coefficients C and k are reported as Monte Carlo means $\pm 1\sigma$ ($n = 5000$ realizations). The coefficient of determination (R^2) and root-mean-square error (RMSE) are calculated from the nominal fit in logarithmic space. Data are filtered using threshold criteria $N_d > N_{d,th}$ and $LWC > LWC_{th}$. The uncertainties of N_d and S_v assumed in the calculations are 30% and 36.6%, respectively. Columns list: Flight ID, $N_{d,th}$, LWC_{th} , C , σC , k , σk , R^2 , RMSE, and sample size (N).

Flight	$N_{d,th}$	LWC_{th}	C	σC	k	σk	R^2	RMSE	N
AC07	10	0	1721.2	192.16	0.802	0.051	0.783	0.645	81
AC07	10	0.01	1646.06	218.54	0.765	0.075	0.657	0.678	71
AC07	10	0.02	1539.65	240.42	0.702	0.098	0.533	0.698	64

AC07	20	0	2014.97	231.49	0.827	0.055	0.958	0.249	77
AC07	20	0.01	1960.94	247.89	0.801	0.073	0.947	0.234	69
AC07	20	0.02	1813.89	252.3	0.731	0.09	0.943	0.193	62
AC07	30	0	1988.67	227.02	0.818	0.055	0.956	0.25	76
AC07	30	0.01	1960.94	247.89	0.801	0.073	0.947	0.234	69
AC07	30	0.02	1813.89	252.3	0.731	0.09	0.943	0.193	62
AC09	10	0	1103.63	193.86	0.758	0.059	0.956	0.244	48
AC09	10	0.01	900.9	217.98	0.642	0.103	0.941	0.169	37
AC09	10	0.02	839.96	246.48	0.593	0.137	0.91	0.173	32
AC09	20	0	1006.72	213.9	0.705	0.084	0.952	0.19	41
AC09	20	0.01	900.9	217.98	0.642	0.103	0.941	0.169	37
AC09	20	0.02	839.96	246.48	0.593	0.137	0.91	0.173	32
AC09	30	0	933.33	218.37	0.662	0.098	0.949	0.167	38
AC09	30	0.01	900.9	217.98	0.642	0.103	0.941	0.169	37
AC09	30	0.02	839.96	246.48	0.593	0.137	0.91	0.173	32
AC11	10	0	1414.52	175.01	0.844	0.075	0.99	0.125	35
AC11	10	0.01	1339.18	180.85	0.785	0.101	0.982	0.125	33
AC11	10	0.02	1294.82	175.18	0.742	0.11	0.98	0.118	32
AC11	20	0	1339.18	180.85	0.785	0.101	0.982	0.125	33
AC11	20	0.01	1339.18	180.85	0.785	0.101	0.982	0.125	33
AC11	20	0.02	1294.82	175.18	0.742	0.11	0.98	0.118	32
AC11	30	0	1339.18	180.85	0.785	0.101	0.982	0.125	33
AC11	30	0.01	1339.18	180.85	0.785	0.101	0.982	0.125	33
AC11	30	0.02	1294.82	175.18	0.742	0.11	0.98	0.118	32
AC14	10	0	1374.34	139.07	0.855	0.056	0.979	0.18	74
AC14	10	0.01	1366.47	152.1	0.844	0.072	0.977	0.166	70
AC14	10	0.02	1294.32	145.45	0.784	0.08	0.972	0.153	65
AC14	20	0	1390.5	146.66	0.862	0.061	0.981	0.164	73
AC14	20	0.01	1366.47	152.1	0.844	0.072	0.977	0.166	70

AC14	20	0.02	1294.32	145.45	0.784	0.08	0.972	0.153	65
AC14	30	0	1355.09	150.79	0.836	0.074	0.975	0.167	69
AC14	30	0.01	1355.09	150.79	0.836	0.074	0.975	0.167	69
AC14	30	0.02	1294.32	145.45	0.784	0.08	0.972	0.153	65
AC17a	10	0	1320.21	95.94	0.849	0.038	0.961	0.271	131
AC17a	10	0.01	1225.93	98.67	0.774	0.054	0.934	0.263	117
AC17a	10	0.02	1168.27	101.36	0.718	0.067	0.9	0.267	108
AC17a	20	0	1254.73	99.58	0.796	0.049	0.947	0.26	121
AC17a	20	0.01	1225.93	98.67	0.774	0.054	0.934	0.263	117
AC17a	20	0.02	1168.27	101.36	0.718	0.067	0.9	0.267	108
AC17a	30	0	1213.02	100.58	0.763	0.055	0.931	0.263	116
AC17a	30	0.01	1213.02	100.58	0.763	0.055	0.931	0.263	116
AC17a	30	0.02	1168.27	101.36	0.718	0.067	0.9	0.267	108
AC17b	10	0	1697.48	157.11	0.841	0.051	0.978	0.201	69
AC17b	10	0.01	1648.07	178.79	0.807	0.079	0.973	0.159	63
AC17b	10	0.02	1600.21	178.1	0.773	0.086	0.967	0.16	61
AC17b	20	0	1654.08	175.36	0.812	0.074	0.975	0.161	64
AC17b	20	0.01	1648.07	178.79	0.807	0.079	0.973	0.159	63
AC17b	20	0.02	1600.21	178.1	0.773	0.086	0.967	0.16	61
AC17b	30	0	1654.08	175.36	0.812	0.074	0.975	0.161	64
AC17b	30	0.01	1648.07	178.79	0.807	0.079	0.973	0.159	63
AC17b	30	0.02	1600.21	178.1	0.773	0.086	0.967	0.16	61
AC18	10	0	1176.15	130.06	0.765	0.048	0.961	0.214	106
AC18	10	0.01	1013.18	134.56	0.676	0.067	0.927	0.212	96
AC18	10	0.02	881.14	130.89	0.582	0.081	0.881	0.211	87
AC18	20	0	1063.6	131.77	0.706	0.06	0.94	0.213	99
AC18	20	0.01	1013.18	134.56	0.676	0.067	0.927	0.212	96
AC18	20	0.02	881.14	130.89	0.582	0.081	0.881	0.211	87
AC18	30	0	1013.18	134.56	0.676	0.067	0.927	0.212	96

AC18	30	0.01	1013.18	134.56	0.676	0.067	0.927	0.212	96
AC18	30	0.02	881.14	130.89	0.582	0.081	0.881	0.211	87
AC19	10	0	534	64.12	0.695	0.05	0.912	0.247	177
AC19	10	0.01	466.78	62.42	0.625	0.059	0.875	0.244	164
AC19	10	0.02	400.16	62.31	0.539	0.072	0.817	0.243	148
AC19	20	0	456.91	61.43	0.614	0.059	0.874	0.24	163
AC19	20	0.01	456.91	61.43	0.614	0.059	0.874	0.24	163
AC19	20	0.02	400.16	62.31	0.539	0.072	0.817	0.243	148
AC19	30	0	425.99	59.82	0.576	0.063	0.847	0.243	157
AC19	30	0.01	425.99	59.82	0.576	0.063	0.847	0.243	157
AC19	30	0.02	400.16	62.31	0.539	0.072	0.817	0.243	148

Table S5. Power-law fit parameters for the relationship $N_d = C \cdot S_l^k$ derived from log-log regression. The coefficients C and k are reported as Monte Carlo means $\pm 1\sigma$ ($n = 5000$ realizations). The coefficient of determination (R^2) and root-mean-square error (RMSE) are calculated from the nominal fit in logarithmic space. Data are filtered using threshold criteria $N_d > N_{d,th}$ and $LWC > LWC_{th}$. The uncertainties of N_d and S_l assumed in the calculations are 30% and 27.6%, respectively. Columns list: Flight ID, $N_{d,th}$, LWC_{th} , C , σC , k , σk , R^2 , RMSE, and sample size (N).

Flight	$N_{d,th}$	LWC_{th}	C	σC	k	σk	R^2	RMSE	N
AC07	10	0	266.51	13.55	0.854	0.039	0.788	0.638	81
AC07	10	0.01	269	16.61	0.848	0.057	0.664	0.671	71
AC07	10	0.02	279.13	22.2	0.817	0.078	0.543	0.691	64
AC07	20	0	293.02	15.35	0.884	0.043	0.958	0.249	77
AC07	20	0.01	294.93	18.34	0.882	0.054	0.948	0.233	69
AC07	20	0.02	309.74	24.01	0.839	0.07	0.942	0.194	62
AC07	30	0	294.72	15.87	0.877	0.042	0.956	0.249	76
AC07	30	0.01	294.93	18.34	0.882	0.054	0.948	0.233	69
AC07	30	0.02	309.74	24.01	0.839	0.07	0.942	0.194	62

AC09	10	0	211.93	14.99	0.802	0.046	0.957	0.243	48
AC09	10	0.01	217.7	15.39	0.731	0.085	0.944	0.166	37
AC09	10	0.02	219.48	16.18	0.717	0.117	0.913	0.169	32
AC09	20	0	215.09	15.29	0.773	0.067	0.953	0.188	41
AC09	20	0.01	217.7	15.39	0.731	0.085	0.944	0.166	37
AC09	20	0.02	219.48	16.18	0.717	0.117	0.913	0.169	32
AC09	30	0	216.99	15.33	0.746	0.081	0.951	0.164	38
AC09	30	0.01	217.7	15.39	0.731	0.085	0.944	0.166	37
AC09	30	0.02	219.48	16.18	0.717	0.117	0.913	0.169	32
AC11	10	0	193.46	18.27	0.907	0.06	0.99	0.121	35
AC11	10	0.01	200.94	24.17	0.88	0.083	0.983	0.12	33
AC11	10	0.02	211.29	27.99	0.847	0.09	0.981	0.114	32
AC11	20	0	200.94	24.17	0.88	0.083	0.983	0.12	33
AC11	20	0.01	200.94	24.17	0.88	0.083	0.983	0.12	33
AC11	20	0.02	211.29	27.99	0.847	0.09	0.981	0.114	32
AC11	30	0	200.94	24.17	0.88	0.083	0.983	0.12	33
AC11	30	0.01	200.94	24.17	0.88	0.083	0.983	0.12	33
AC11	30	0.02	211.29	27.99	0.847	0.09	0.981	0.114	32
AC14	10	0	193.24	11.46	0.919	0.043	0.981	0.173	74
AC14	10	0.01	192.2	13.05	0.929	0.053	0.979	0.157	70
AC14	10	0.02	203.97	16.47	0.883	0.062	0.974	0.147	65
AC14	20	0	190.74	11.89	0.935	0.047	0.983	0.157	73
AC14	20	0.01	192.2	13.05	0.929	0.053	0.979	0.157	70
AC14	20	0.02	203.97	16.47	0.883	0.062	0.974	0.147	65
AC14	30	0	193.31	13.75	0.925	0.056	0.977	0.158	69
AC14	30	0.01	193.31	13.75	0.925	0.056	0.977	0.158	69
AC14	30	0.02	203.97	16.47	0.883	0.062	0.974	0.147	65
AC17a	10	0	189.08	7.94	0.909	0.029	0.964	0.261	131

AC17a	10	0.01	200.53	10.66	0.862	0.04	0.938	0.254	117
AC17a	10	0.02	208.84	14.3	0.831	0.052	0.907	0.258	108
AC17a	20	0	198.01	9.81	0.872	0.037	0.951	0.251	121
AC17a	20	0.01	200.53	10.66	0.862	0.04	0.938	0.254	117
AC17a	20	0.02	208.84	14.3	0.831	0.052	0.907	0.258	108
AC17a	30	0	202.61	10.9	0.853	0.042	0.935	0.254	116
AC17a	30	0.01	202.61	10.9	0.853	0.042	0.935	0.254	116
AC17a	30	0.02	208.84	14.3	0.831	0.052	0.907	0.258	108
AC17b	10	0	236.59	14.36	0.893	0.039	0.979	0.195	69
AC17b	10	0.01	234.73	19.91	0.906	0.061	0.976	0.15	63
AC17b	10	0.02	242.52	22.71	0.883	0.068	0.97	0.151	61
AC17b	20	0	235.49	18.71	0.903	0.057	0.977	0.153	64
AC17b	20	0.01	234.73	19.91	0.906	0.061	0.976	0.15	63
AC17b	20	0.02	242.52	22.71	0.883	0.068	0.97	0.151	61
AC17b	30	0	235.49	18.71	0.903	0.057	0.977	0.153	64
AC17b	30	0.01	234.73	19.91	0.906	0.061	0.976	0.15	63
AC17b	30	0.02	242.52	22.71	0.883	0.068	0.97	0.151	61
AC18	10	0	204.42	8.54	0.827	0.036	0.962	0.21	106
AC18	10	0.01	210.96	9.57	0.77	0.051	0.93	0.208	96
AC18	10	0.02	221.76	11.57	0.699	0.066	0.885	0.207	87
AC18	20	0	208.54	9.32	0.787	0.047	0.942	0.209	99
AC18	20	0.01	210.96	9.57	0.77	0.051	0.93	0.208	96
AC18	20	0.02	221.76	11.57	0.699	0.066	0.885	0.207	87
AC18	30	0	210.96	9.57	0.77	0.051	0.93	0.208	96
AC18	30	0.01	210.96	9.57	0.77	0.051	0.93	0.208	96
AC18	30	0.02	221.76	11.57	0.699	0.066	0.885	0.207	87
AC19	10	0	126.59	4.38	0.784	0.038	0.914	0.244	177
AC19	10	0.01	127.24	4.34	0.736	0.046	0.878	0.241	164
AC19	10	0.02	128.75	4.35	0.674	0.059	0.82	0.241	148

AC19	20	0	127.43	4.34	0.724	0.047	0.876	0.238	163
AC19	20	0.01	127.43	4.34	0.724	0.047	0.876	0.238	163
AC19	20	0.02	128.75	4.35	0.674	0.059	0.82	0.241	148
AC19	30	0	127.99	4.32	0.693	0.051	0.85	0.24	157
AC19	30	0.01	127.99	4.32	0.693	0.051	0.85	0.24	157
AC19	30	0.02	128.75	4.35	0.674	0.059	0.82	0.241	148

Table S6. Power-law fit parameters for the relationship $N_d = C \cdot S_c^k$ derived from log–log regression. The coefficients C and k are reported as Monte Carlo means $\pm 1\sigma$ ($n = 5000$ realizations). The coefficient of determination (R^2) and root-mean-square error (RMSE) are calculated from the nominal fit in logarithmic space. Data are filtered using threshold criteria $N_d > N_{d,th}$ and $LWC > LWC_{th}$. The uncertainties of N_d and S_c assumed in the calculations are 30% and 28.5%, respectively. Columns list: Flight ID, $N_{d,th}$, LWC_{th} , C , σC , k , σk , R^2 , RMSE, and sample size (N).

Flight	$N_{d,th}$	LWC_{th}	C	σC	k	σk	R²	RMSE	N
AC07	10	0	246.01	12.94	0.85	0.04	0.787	0.639	81
AC07	10	0.01	249.2	16.59	0.841	0.058	0.663	0.672	71
AC07	10	0.02	260.33	22.76	0.807	0.081	0.542	0.691	64
AC07	20	0	269.85	14.76	0.879	0.044	0.958	0.249	77
AC07	20	0.01	272.28	18.1	0.875	0.056	0.948	0.233	69
AC07	20	0.02	288.17	24.58	0.83	0.072	0.942	0.194	62
AC07	30	0	271.65	15.23	0.872	0.044	0.956	0.249	76
AC07	30	0.01	272.28	18.1	0.875	0.056	0.948	0.233	69
AC07	30	0.02	288.17	24.58	0.83	0.072	0.942	0.194	62
AC09	10	0	194.3	13.42	0.798	0.047	0.957	0.243	48
AC09	10	0.01	201.34	14.07	0.723	0.087	0.943	0.166	37
AC09	10	0.02	203.71	15.63	0.706	0.12	0.913	0.17	32
AC09	20	0	197.88	13.73	0.767	0.068	0.953	0.188	41

AC09	20	0.01	201.34	14.07	0.723	0.087	0.943	0.166	37
AC09	20	0.02	203.71	15.63	0.706	0.12	0.913	0.17	32
AC09	30	0	200.33	13.94	0.739	0.082	0.951	0.164	38
AC09	30	0.01	201.34	14.07	0.723	0.087	0.943	0.166	37
AC09	30	0.02	203.71	15.63	0.706	0.12	0.913	0.17	32
AC11	10	0	178.21	18.02	0.901	0.061	0.99	0.121	35
AC11	10	0.01	186.53	24.5	0.871	0.085	0.983	0.12	33
AC11	10	0.02	197.14	28.73	0.837	0.092	0.981	0.114	32
AC11	20	0	186.53	24.5	0.871	0.085	0.983	0.12	33
AC11	20	0.01	186.53	24.5	0.871	0.085	0.983	0.12	33
AC11	20	0.02	197.14	28.73	0.837	0.092	0.981	0.114	32
AC11	30	0	186.53	24.5	0.871	0.085	0.983	0.12	33
AC11	30	0.01	186.53	24.5	0.871	0.085	0.983	0.12	33
AC11	30	0.02	197.14	28.73	0.837	0.092	0.981	0.114	32
AC14	10	0	176.81	11.14	0.914	0.045	0.981	0.174	74
AC14	10	0.01	176.04	12.88	0.922	0.055	0.979	0.158	70
AC14	10	0.02	188.13	16.62	0.875	0.064	0.974	0.147	65
AC14	20	0	174.38	11.65	0.929	0.049	0.983	0.157	73
AC14	20	0.01	176.04	12.88	0.922	0.055	0.979	0.158	70
AC14	20	0.02	188.13	16.62	0.875	0.064	0.974	0.147	65
AC14	30	0	177.23	13.63	0.917	0.057	0.977	0.159	69
AC14	30	0.01	177.23	13.63	0.917	0.057	0.977	0.159	69
AC14	30	0.02	188.13	16.62	0.875	0.064	0.974	0.147	65
AC17a	10	0	173.11	7.66	0.903	0.03	0.964	0.262	131
AC17a	10	0.01	185.21	10.82	0.853	0.043	0.938	0.255	117
AC17a	10	0.02	194.26	14.82	0.821	0.055	0.906	0.259	108
AC17a	20	0	182.36	9.74	0.865	0.038	0.95	0.252	121
AC17a	20	0.01	185.21	10.82	0.853	0.043	0.938	0.255	117
AC17a	20	0.02	194.26	14.82	0.821	0.055	0.906	0.259	108

AC17a	30	0	187.33	11.03	0.845	0.044	0.935	0.254	116
AC17a	30	0.01	187.33	11.03	0.845	0.044	0.935	0.254	116
AC17a	30	0.02	194.26	14.82	0.821	0.055	0.906	0.259	108
AC17b	10	0	217.89	13.9	0.889	0.04	0.979	0.196	69
AC17b	10	0.01	217.1	20.02	0.898	0.063	0.976	0.151	63
AC17b	10	0.02	225.27	23.23	0.873	0.07	0.97	0.152	61
AC17b	20	0	217.62	18.73	0.895	0.059	0.977	0.153	64
AC17b	20	0.01	217.1	20.02	0.898	0.063	0.976	0.151	63
AC17b	20	0.02	225.27	23.23	0.873	0.07	0.97	0.152	61
AC17b	30	0	217.62	18.73	0.895	0.059	0.977	0.153	64
AC17b	30	0.01	217.1	20.02	0.898	0.063	0.976	0.151	63
AC17b	30	0.02	225.27	23.23	0.873	0.07	0.97	0.152	61
AC18	10	0	188.64	8	0.822	0.037	0.962	0.21	106
AC18	10	0.01	196.19	9.42	0.762	0.053	0.929	0.209	96
AC18	10	0.02	208.19	11.92	0.688	0.068	0.885	0.208	87
AC18	20	0	193.44	9.02	0.781	0.048	0.942	0.209	99
AC18	20	0.01	196.19	9.42	0.762	0.053	0.929	0.209	96
AC18	20	0.02	208.19	11.92	0.688	0.068	0.885	0.208	87
AC18	30	0	196.19	9.42	0.762	0.053	0.929	0.209	96
AC18	30	0.01	196.19	9.42	0.762	0.053	0.929	0.209	96
AC18	30	0.02	208.19	11.92	0.688	0.068	0.885	0.208	87
AC19	10	0	115.44	3.86	0.777	0.039	0.914	0.245	177
AC19	10	0.01	116.76	3.86	0.726	0.048	0.878	0.242	164
AC19	10	0.02	119.15	4.02	0.661	0.061	0.82	0.241	148
AC19	20	0	117.09	3.86	0.715	0.048	0.876	0.238	163
AC19	20	0.01	117.09	3.86	0.715	0.048	0.876	0.238	163
AC19	20	0.02	119.15	4.02	0.661	0.061	0.82	0.241	148
AC19	30	0	118.08	3.91	0.683	0.052	0.85	0.241	157

AC19	30	0.01	118.08	3.91	0.683	0.052	0.85	0.241	157
AC19	30	0.02	119.15	4.02	0.661	0.061	0.82	0.241	148