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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Cloud-top microphysics evolution in the Gamma phase space from a modeling perspective" *by* Lianet Hernández Pardo et al.

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Authors response to Anonymous Referee #1

(Comment) This manuscript presents a numerical exercise that adjusted the gamma size distribution parameters in a bulk microphysics scheme based on the fitted gamma parameter values simulated by a 1D kinematic framework using the TAU bin microphysics scheme initiated by a sounding from the ACRIDICON-CHUVA (what is the full name it) campaign. The authors claimed that the so-called "gamma phase space" is useful for evaluating and improving microphysics schemes. I found many aspects of the manuscript such as assumptions, concepts, logics, interpretations and presentations are questionable. I do not recommend this manuscript to be published in ACP. The main concerns and some technical comments are listed in the following:

(Answer) We would like to thank Anonymous Referee #1 for taking the time to analyze our work and pinpoint potential improvements. Here we provide a detailed response to the issues raised by Anonymous Referee #1. While we agree that the manuscript can be significantly improved based on the comments, we believe there is merit in publishing it given its novelty factor and the potential future research topics it enables.

Major points:

1. **(Comment)** The concept of using "pseudo forces" representing microphysical processes and cloud dynamics to explain the trajectory in "gamma phase space" Cecchini et al. (2017) makes zero sense for the observational data. The cloud samples measured by the instruments at different times are combinations of hydrometeors experienced so many different microphysical and dynamical pathways. The derived gamma parameters based on these measurements are in no way determined by the "pseudo forces" that are only meaningful in a Lagrangian sense. It is ok to show the derived parameter values in the phase space. But it is not appropriate to interpret the relationships among them using the "pseudo-force" concept.

1. **(Answer)** While the work of Cecchini et al. (2017) has its shortcomings, as any aircraft-based interpretation of DSD measurements, we definitely disagree with this first statement by Anonymous Referee #1.

Firstly, Amazonian clouds present a fairly uniform daily cycle: when you analyze animated satellite images for the region throughout several days, the "pulsing" aspect of convection is readily observable. Except on squall lines occasions (that can originate as far as the Atlantic Coast to the East), convection is primarily driven by differential heating of the surface (favored in regions with slight elevation – Machado et a. (2017))

and the cumulus field evolves from there. Therefore, when you plan an aircraft-based experimental campaign in the Amazon, you can choose to start flying by the time clouds are growing – note that ACRIDICON-CHUVA flights started in the late morning or early afternoon because of that. In this way it is possible to capture growing convective elements, especially when you primarily probe cloud tops – as done in ACRIDICON-CHUVA – and when you focus on updrafts – as done in Cecchini et al. (2017). The assumption that a snapshot of cloud-tops at various stages of the convection development equals the evolution of the top of an individual cloud that grows vertically was previously employed by Rosenfeld et al. (2008) to retrieve T-r_e relationships that infer the vigor of severe convective storms.

What Cecchini et al. (2017) did was to use the altitude of DSD measurements as proxy for the time evolution of the clouds, which is justified given the specific configuration of the flight strategies. This proxy was used to generate the hypothesis that the DSD evolution can be understood as pseudo-forces in the Gamma phase space. This is as far as the Cecchini et al. (2017) could go, and no quantifications were provided because: 1) while the flight strategies serve as proxies for cloud evolution (in a semi-Lagrangean way) and certainly provide interesting insights for cloud DSD evolution, the uncertainties of the methodology itself impedes such quantifications; 2) the authors used a relatively simple conceptual model to study the trajectories – namely the condensation + collision-coalescence balance –, as a first step into the Gamma phase space, but other processes such as mixing should be considered for proper quantifications. Additionally, contemporary studies such as Yang et al. (2017) show that other processes may also contribute to DSD broadening aside from collision-coalesce as discussed in Cecchini et al. (2017). Our study aims to tackle exactly the shortcomings of Cecchini et al. (2017) by using a 1D model where there is more control over the conditions creating the DSDs being analyzed. In this way, the pseudo-forces approach can be directly tested.

2. **(Comment)** As shown in McFarquhar et al. (2015), just one part of the observational

uncertainties (counting uncertainty) lead to big ranges of gamma parameter values that describe the same equally realizable particle size distribution (PSD). The parameter uncertainty ranges can be comparable or greater than the differences between those derived by different measurement points, especially when PSD deviates from gamma distribution.

2. **(Answer)** As estimated by Cecchini et al. (2017), specifically in their Fig. 10, the observed DSDs used to generate the pseudo-forces hypothesis most likely evolve beyond the ellipsoids in the Gamma phase space proposed by McFarquhar et al. (2015) when we consider an instrument uncertainty of 10%. So, overlapping the corresponding ellipsoids through the entire path would allow to obtain the same conclusions about the DSD evolution. Also see the authors response to major point 6) of the Anonymous Referee #4 in the discussions of Cecchini et al. (2017):

https://www.atmos-chem-phys-discuss.net/acp-2017-185/acp-2017-185-AC4-supplement.pdf

In our case, a measure of the uncertainties contained in each point represented by big markers in Fig. 2a of the manuscript can come from the dispersion of the small markers that correspond to individual DSDs at each cloud-top height. It can be observed, analogously to the analysis of Cecchini et al. (2017), that the entire phase space trajectory evolves beyond the spread of the points at each level (symbolized by the color scale).

That being said, we believe there is a fundamental difference between our approach and the one proposed by McFarquhar et al. (2015) – both of them are valid and highlight different aspects of cloud microphysics.

The McFarquhar et al. (2015) approach originates from observational uncertainties and can supposedly help improve models with Monte Carlo assumptions in the future. While we agree that this is an adequate solution from a statistical/Monte Carlo standpoint, we disagree that it prevents a physically-based analysis such as the one

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proposed here. The present work is not particularly interested in random movements in the Gamma phase space that originate from random DSD variabilities around a specific point. Rather, we want to understand what the physics behind the movements in the space is, which is equivalent to the knowledge of how one point moves from position A to position B. Additionally, when working with a deterministic model, there is no direct benefit on generating random movements to conform to observational characteristics. Instead, we focus on idealized trajectories in the phase space and how they can be related to microphysical processes.

To illustrate the complementary nature of both approaches, let us consider the following specific case. Figure 1 below roughly represents Fig. 5b from McFarquhar et al. (2015), where we substituted the ellipsoid projection with three straight lines (black continuous and dashed lines). The colors represent different effective diameter (D_{eff}, calculated as $\frac{\mu+3}{\Lambda}$) values in μm, where the region inside the black lines is highlighted. The solid line represents the major axis of the ellipsoid projection (note we limited the y axis to 3×10^4 m^{-1} for clarity), while the dashed lines delimit upper and bottom boundaries.

A statistical view of Fig. 1 might highlight the spread in D_{eff} values inside the ellipsoid, which can be associated to the underlying uncertainties of the application. However, a complementary and physically-based analysis might propose to understand what straight lines even mean in this space. It can be shown that every straight line conserves the averaged diameter D_j of the form:

$$D_j = \frac{M_j}{M_{j-1}} = \frac{\mu + j}{\Lambda} \tag{1}$$

Where M_j is the j'th moment of the DSD (when $j = 3$, $D_j = D_{eff}$). Eq. 1 basically states that the ratio between consecutive moments is conserved in straight lines in the $\mu - \Lambda$ space. The ratio between moments further apart should then be represented by higher order polynomials. If we substitute $\Lambda = a + b\mu$ into Eq. 1, differentiate with respect to μ and equate the result to zero, we can find the moment ratio being conserved in any straight line by:

$$j = \frac{a}{b} \tag{2}$$

Using Eq. 2, we calculate $j = 2.2, 3.4, 4.6$ for the bottom, mid and top lines in Fig. 1. From this we conclude that the spread of D_{eff} values inside the colored area stems from differences in the a and b coefficients. Those coefficients can also be understood as the degree of deviation from the exponential case and Eq. 2 can be rewritten as

$$j = \frac{\Lambda_{exp}\mu}{\Lambda - \Lambda_{exp}} \tag{3}$$

Where we note that $b = \frac{\Lambda - \Lambda_{exp}}{\mu}$ and $a = \Lambda_{exp}$ and Λ_{exp} is the Λ of an exponential function ($\mu = 0$). Another consequence from Eqs. 2 and 3 is that it is possible to fix j and find all the lines that conserve D_j, thus producing contour lines similar to Fig. 1 and ultimately a continuous surface.

All of the explanations above have the intention of highlighting the possibilities of treating the Gamma phase space as a physical entity as well as a statistical one. Additionally, it shows that there are preferential shapes on the phase space depending on the underlying physics of the problem being analyzed. The ellipsoid shape is justified in observational studies because of the proximity of the DSDs in the phase space. However, different points inside the ellipsoids may be related to different physical processes, or different “histories” that drove the points there. Further analysis that better explain the correlations between the Monte Carlo and deterministic approaches in the Gamma phase space are surely encouraged.

3. **(Comment)** The authors may argue that McFarquhar et al. (2015) focused on mixed-

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phase while Cecchini et al. (2017) focused on liquid phase. However, the small range of the cloud droplet size ($< 50\mu m$) should apply the incomplete gamma distribution fit rather than the complete gamma fit. Using the complete gamma fit results in higher uncertainties in the phase space.

3. **(Answer)** The complete/incomplete Gamma discussion was added to the Cecchini et al. (2017) paper as part of the revision process. See the discussion in the major point 4) here:

https://www.atmos-chem-phys-discuss.net/acp-2017-185/acp-2017-185-AC5-supplement.pdf

The overall conclusion is that the relation between different DSD moments is conserved between the incomplete and complete approaches, even though the values of the moments themselves are different. In other words, the complete- and incomplete-Gamma trajectories are most likely parallel and so are the pseudo-forces.

We mentioned the 50 μm restriction for droplets diameter to be coherent with the analysis of Cecchini et al. (2017), however, there is no significant quantity of rain drops in the simulated cloud-top. Figure 2 shows the DSDs for some cloud-top heights, averaged for time-steps where the model stayed in the same maximum height. It can be seen that, for diameters larger that 30 μm, there are less than one droplet per cm^3, actually a few droplets per m^3.

4. **(Comment)** The ranges of the fitted μ and Λ parameters based on TAU simulation span at least an order of magnitude wider in the phase space compared to the observed counterparts (Fig. 2). These high simulated values are unphysical and never observed. How can such unphysical representations of clouds serve as a base to improve the bulk microphysics?

4. **(Answer)** The fact that high values of μ and Λ (and low values of N_0) are not observed does not necessarily mean they are unphysical. It may only mean that our

current instrument setup does not detect them. Note that those values occur close to cloud base and they get closer to the observed values as the cloud grows. As commented in the manuscript (section 3.1, third paragraph), the observed droplets existed for much longer than the modeled ones, otherwise the cloud would not even be visible from the airplane. The definition of an objective threshold to define the cloud boundaries (see answer to question 6) allows us to sample cloud stages that may not be considered in the observations. Moreover, Cecchini et al. (2017) showed a 200m-averaged data, while we use a 50m grid-spacement, therefore representing a more detailed path in the gamma phase space.

The question now is: what physical processes produce such high μ and Λ values? As mentioned before, this type of DSD appears mostly close to cloud base and the high shape and curvature parameters produce very narrow distributions. They are basically a result of freshly activated CCNs, where the droplets cover only a small number of bins. In other words, the cloud is just being formed and there was not enough time for growth mechanisms to occur.

The latter is illustrated in Fig. 3. It shows the actual DSD and the fitted gamma function corresponding to the first point in the path of Fig. 2a of the main manuscript.

The sampling strategy determines the localization of the curve in the gamma phase space. So it is possible to increase the similarity between the observed and simulated paths if we modify the cloud-top definition and the minimum altitude above cloud-base at which we start to track the cloud-top in the simulation. Consequently, moving the trajectory inward or outward the cloud avoids the extreme, questioned values that correspond to non-easily observed stages of cloud development (Fig. 4). We have to keep in mind that the model setup is highly idealized, therefore its prognostics are not meant to be quantitatively precise. Conversely, the intent of using such tools is to study specific processes that can help build a conceptual model rather than trying to faithfully reproduce nature. The important thing to note, independently of the sampling strategy in the simulation, is the qualitative similarity between the modeled and observed trajectories, and the reasons for that should be explored.

As we mentioned in the sixth paragraph, section 3.2, we are aware that such high values of μ obtained at the beginning of the TAU cloud does not perform well in the bulk scheme, possibly because this kind of schemes include more observation-based features than bin schemes. For that reason, we restricted the expression for μ that was applied, citing the manuscript: “For now, taking into account that the thompson08 scheme considers a variation of μ between 2 for continental and 15 for maritime, according to the general dispersion characteristics from Martin et al. (1994) and the results of Cecchini et al. (2017), we defined a threshold of 20 as an upper bound on μ for the tests implemented here.” We showed and discussed the entire evolution in the gamma space, but we did not use those extreme and somehow questionable values of μ, Λ and N_0 in the final expression for μ.

5. **(Comment)** Bin microphysics schemes are conceptually more realistic but not practically more realistic. The bin microphysics intercomparison study by Xue et al. (2017) demonstrates that the uncertainties associated with bin microphysics schemes are similar if not greater than those in bulk schemes. A new study by Morrison et al. (2018) (JAS under review now) shows that the combined advection in space (Eulerian framework) and in bin dimension (either mass or diameter) of the cloud droplet condensation process inevitably broadens the simulated PSD while the liquid water content and mean droplet diameter are accurately predicted. The model setup is similar to what is used in this work. The derived gamma parameters based on the TAU simulation did not correspond to the actual physics that lead to the observed values.

5. **(Answer)** We understand that bin models, despite having a higher accuracy on the representation of physical processes, may not be able to fully represent clouds in nature. They still have their internal assumptions and the usually idealized input data prevents realistic representations. What the Xue et al. (2017) paper notes is that different bin schemes produce similar systems overall, that have significantly different internal structure. One of the main reasons for that was pointed out to be the repre-

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sentation of ice processes. Note that our present work deals exclusively with warm processes, where the processes are much less complex. Either way, we are not trying to precisely represent the observed cloud – otherwise we would not have chosen a 1D model. The idea behind the model choice is to have a tool that precisely calculates the baseline physical processes, while limiting complex and non-linear interactions between microphysics and dynamics. The aim is to establish the basic concepts on the interpretation of the Gamma phase space.

We cannot comment directly on the Morrison et al. (2018) paper, or attest to its methodology, because we have no access to it. However, we also noted the pattern of widening DSDs even with little or no collision-coalescence growth. Figures 4 and 5 (main manuscript) address this issue by segregating the pseudo-forces. Taking into account the processes resolved by the model, we noted two mechanisms that can widen the DSD during the early stages of the cloud where there is no collection growth yet. Both advection and condensational growth were at least partly responsible for the DSD widening in our case, determining a path in the gamma phase space that closely resembles the observed in Cecchini et al. (2017). We will surely look forward for the publication of the Morrison et al. (2018) paper to study additional features that can help explain our results – particularly the advection in bin dimension.

6. **(Comment)** How is the cloud top defined in this work? All discussions and analysis are around “cloud-top” but no clear definition is stated. A profile plot of the initial relative humidity is helpful. The time evolution of the simulated cloud water and rain water profiles should also be provided (profiles of q_c, n_c, q_r and n_r in every 5 minutes would work).

6. **(Answer)** Figure 5 shows q_c (g/kg), N_c (cm^{-3}), D_{eff} (μm) and relative humidity (RH) (%) for the entire simulation. See that the upward advection causes a maximum of N_c at cloud-top for all times. As droplets ascend and mix with new droplets, they grow by diffusion of vapor and, to a lesser extent, by collision-coalescence. As a consequence, D_{eff} and q_c are larger in upper levels at the last times of the simulation.

There is no rain class in the TAU scheme, instead, the bins are intended to span through all the liquid water spectrum. The above figures include the information from all the bins, so they theoretically include both cloud and rain droplets. Defining a size threshold, it would be possible to discriminate between rain and cloud water. However, as can be observed in Fig. 2, there is no significant quantity of rain drops in the cloud-top. So Fig. 5 represent basically cloud droplets.

The cloud-top was defined as the last model level, from surface to top, where the droplets concentration was larger than 100 per cm^3. As we commented in the manuscript (section 3.1, fourth paragraph), variations in environmental characteristics, exemplified by the aerosol number concentration (Fig.3 in the manuscript), changes the localization of the path in the gamma phase space. A similar effect can be obtained if we vary the droplets number concentration threshold that defines cloud-boundaries. The variations of the restricted path in the gamma phase space are shown in Fig. 4. Despite several aspects modulates the similarity of the simulated gamma path with the measured values of Cecchini et al. (2017), they keep the same trend to move from high Λ and μ, and small N_0, toward smaller Λ and μ, with higher N_0, which represents the evolution from incipient to more developed DSDs in both simulation and observations. Again, our intention was not to obtain accurately coincident paths, we wanted to emphasize the general trend that has to be guaranteed in order to be physically coherent.

The definition of cloud-top, as well as the time evolution of q_c, N_c and D_{eff} were added to the manuscript.

7. **(Comment)** Without knowing how the data were calculated in Fig. 5, I am still surprised to see the author claim that the advection increases the number and size of the cloud droplets in the cloud top (Fig. 5c and d). Where are the sources of these large droplets?

7. **(Answer)** The markers in Figure 5a (main manuscript) represents the same data

that big markers in Fig. 2a (main manuscript): time-averages of the cloud-top DSDs for the times-steps when the cloud-top stayed at the same level of the model vertical domain, but in this case for two bulk properties of the DSD, instead of the three parameters of the fitted gamma function. Analogously, we constructed Fig. 5b,c and d (main manuscript), limited to some points within each regime defined in Fig. 5a (main manuscript). The vectors were represented in the same way than in Fig. 4 (main manuscript): linking initial and final stages due to each microphysics or advection processes, but in the case of Fig. 5 (main manuscript), they represent averaged initial and final states for the times the cloud-top remained in the same level, i.e. they represent the time-averaged effect of each process for a constant cloud-top height. We added this explanation to the manuscript, for clarity.

We commented in section 3.1, sixth paragraph, regarding the information represented in Fig. 4 (main manuscript), that the advection produced a sink effect. That occurs because it refers to a point that is fixed at 1650 m height above surface, and therefore near to cloud-base. At cloud-base, the content that the advection mechanism takes away surpasses what it brings from the inferior layer. Conversely, at upper levels, such as the ones represented in Fig.5c and d (main manuscript), there is more content to bring from below the layer, and the advection produces a net source effect. To increase the effective diameter, there is no need for larger drops, a bigger quantity of the largest ones that already exist is sufficient. Also, note that the effective diameter is the ratio between two DSD moments of consecutive order (the second and third moments), the higher one being in the numerator. The higher the order of the moment, the more weight for larger droplets. So, if we increase the same amount of droplets for every bin, higher order moments will increase faster than smaller ones. Therefore, the effective diameter can increase even if every bin number concentration increases proportionally.

8. **(Comment)** The μ-q_c relationship (Fig. 7a) was found in the TAU data at cloud top. Was Eq. 11 applied to the Thompson scheme everywhere or just at cloud top in the simulation that generates Fig. 8? The μ-q_c relationship outside of cloud top can be

completely different. The observed μ-q_c relationship can be very different than the bin results. The way to “improve” the bulk scheme does not necessarily need the gamma phase space concept.

8. **(Answer)** Yes, the μ-q_c relationship outside of cloud-top can be completely different. Because the μ-q_c was found in the TAU data at cloud-top, we agree that, a priori, it should only be applicable at cloud-top. Note that Eq. 11 tends to Eq. 3 when q_c tends to infinity, as we explain in the manuscript (section 3.2, fourth paragraph), because we just added a term that is inversely proportional do q_c. Therefore, toward the interior of the cloud, as q_c increases, the introduced modification stops making a difference, not affecting the way μ was previously determined in thompson08 scheme (also explained in section 3.2, ninth paragraph).

We concur with Anonymous Referee #1 that the observed μ-q_c relationship can be very different than the one obtained from bin schemes. However, a common problem in modelling microphysics processes comes from the difficulty to obtain direct measurements of hydrometeors to improve theory and to perform direct comparisons, which brings us back to item 1 of this document. As a consequence, microphysics parameterizations has to be evaluated based on secondary quantities, such as precipitation estimated from remote sensors, etc. On the other hand, despite its shortcomings, bin schemes are considered more realistic because they use a reduced number of simplifications with respect to bulk approaches. As a consequence, they are usually considered as a reference to adjust bulk parameterizations. The proposed μ-q_c relationship satisfies the objective of inducing an already validated bin feature –the cloud-top trajectory in the gamma phase space– into a simpler scheme that was proven to misrepresent it. So we are not only reproducing a random characteristic of a bin scheme, we are trying to bring an observed particularity to a bulk scheme, using the bin parameterization as a tool.

The phase space concept is a tool, as many others usually addressed in science to better visualize and understand physical processes. Maybe we could arrive to the same result without mentioning the gamma phase space, but it would increase the difficulty of otherwise simpler interpretations. What is actually needed is a correct description of gamma parameters, without it almost all microphysics calculations remains unrealistic and unphysical. We believe that characterizing the gamma phase space mathematically and physically is a worthwhile step in that sense.

Technical points:

1. **(Comment)** Please add projections on the 3D plots.

1. **(Answer)** Projections were added in all 3D plot, except for Fig. 4b, where projections would hamper the visualization.

2. **(Comment)** More plots on the simulated cloud properties will be helpful.

2. **(Answer)** Plots on the simulated q_c, N_c and D_{eff} were included in the manuscript.

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Please also note the supplement to this comment:
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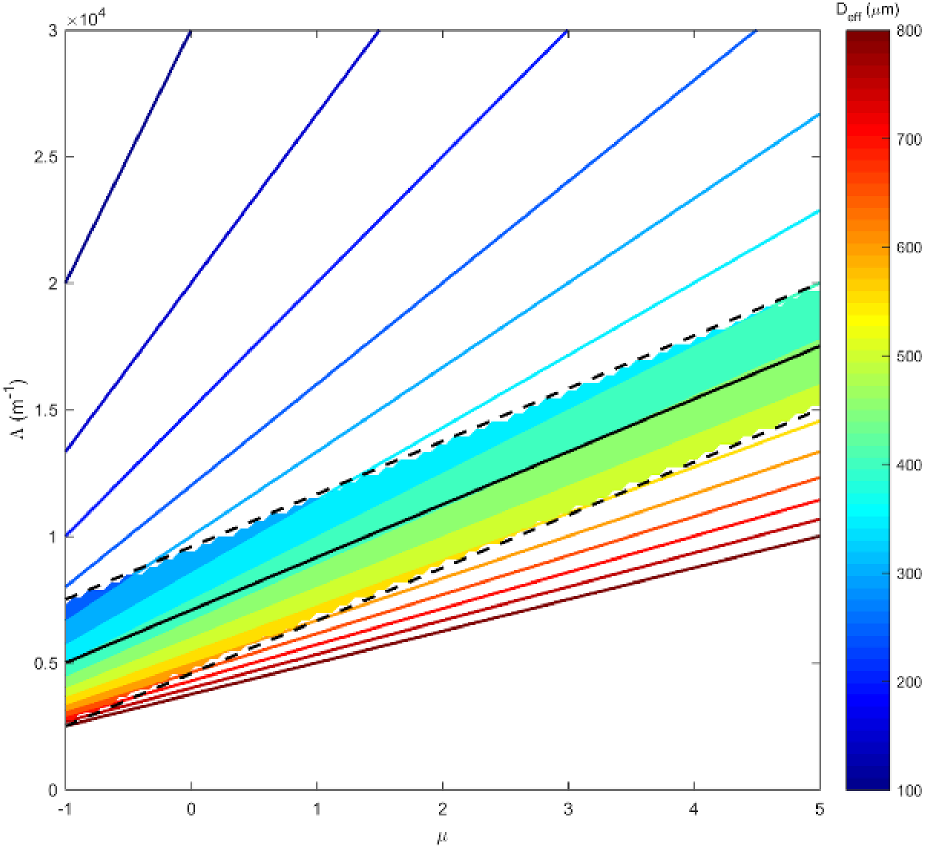

Fig. 1. An adaptation of Fig. 5b in McFarquhar et al. (2015)

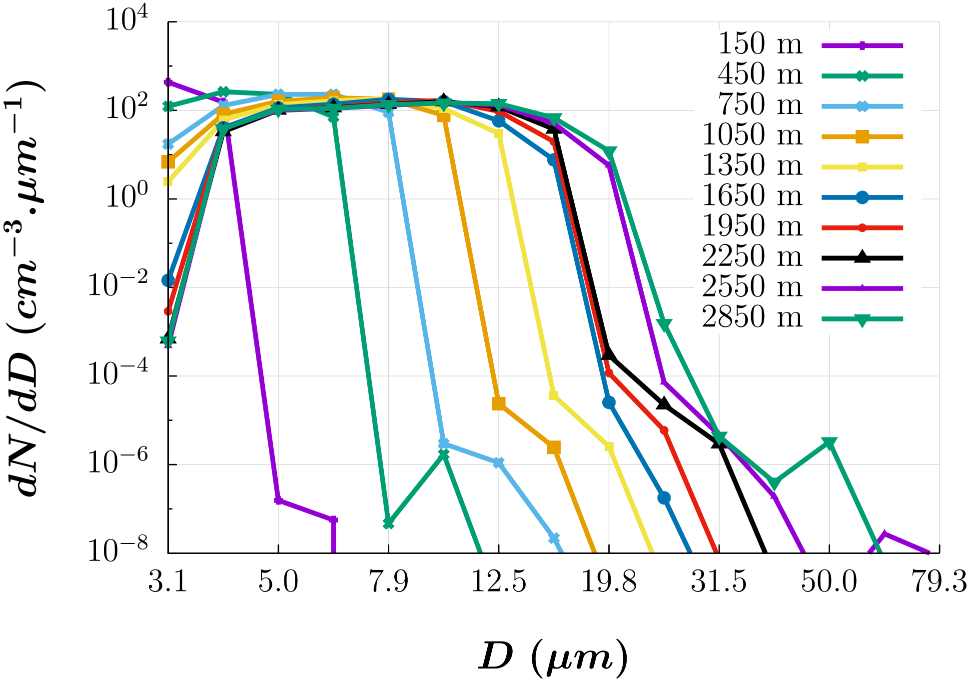

Fig. 2. Examples of the simulated cloud-top DSDs

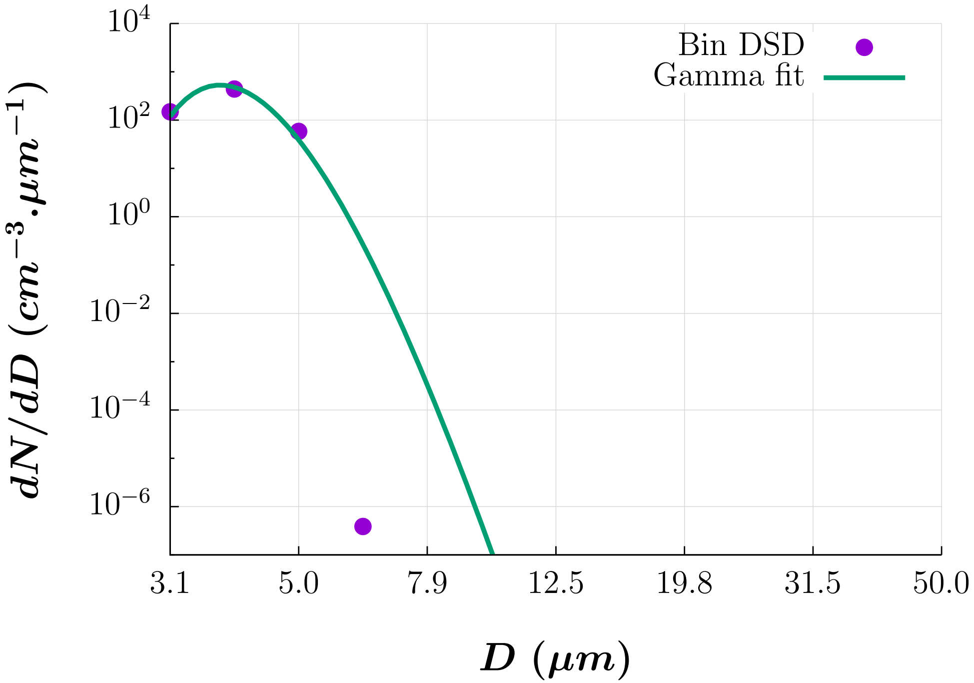

Fig. 3. Droplet size distribution corresponding to the point that is closer to cloud-base in Fig. 2a of the main manuscript

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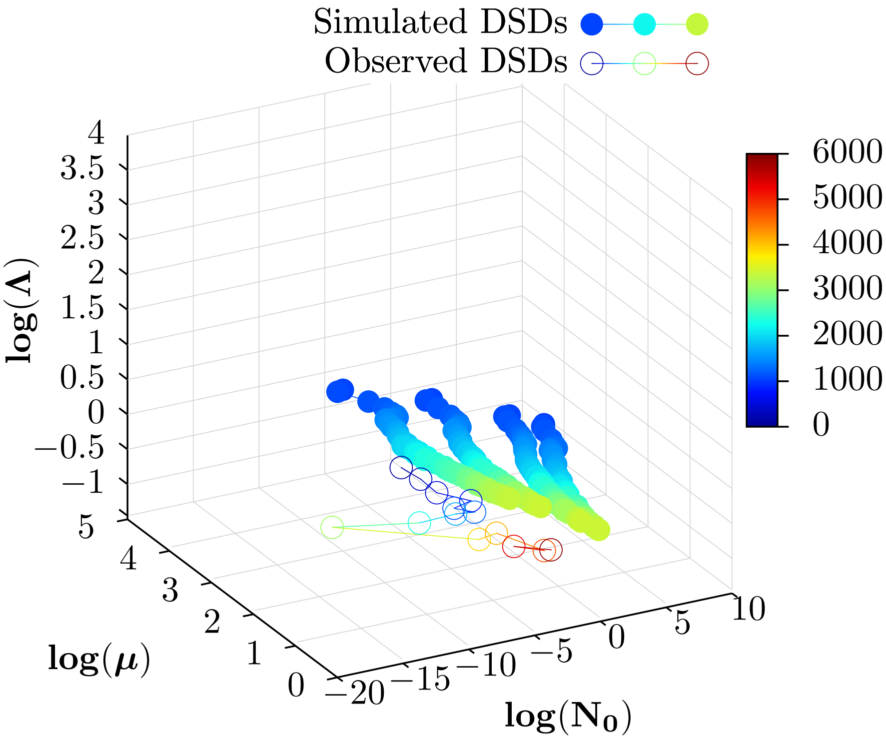
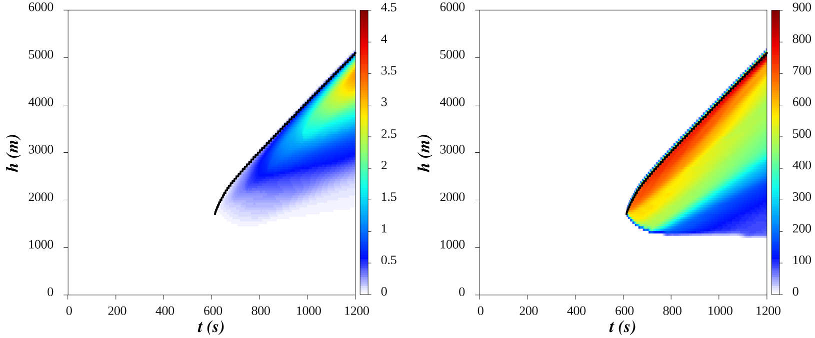
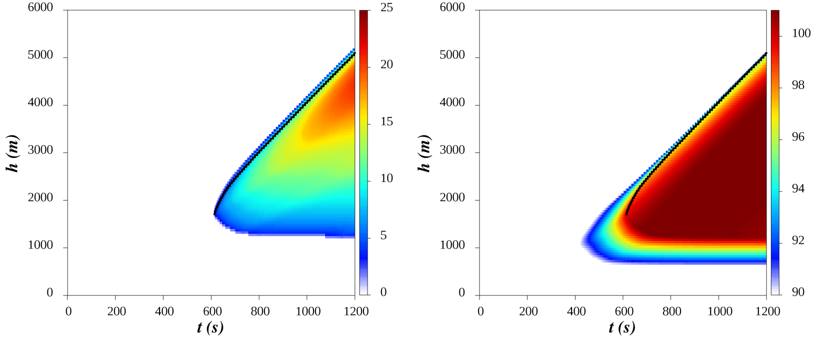


Fig. 4. Comparison between the observed trajectory and the modeled ones, using different sampling strategies and avoiding the youngest stages of the cloud.



(a) q_c (g/kg) (b) N_c (cm^{-3})



(c) D_{eff} (μm) (d) RH (%)

Fig. 5. Evolution of cloud properties profiles for the TAU simulation

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