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Interactive comment on "Illustration of microphysical processes in Amazonian deep convective clouds in the Gamma phase space: Introduction and potential applications" *by* Micael A. Cecchini et al.

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Major comments:

(Comment) This paper uses fits of measured cloud droplet size distributions (DSDs) in gamma phase space to investigate warm-phase microphysical cloud properties and the role of "pseudo-forces" in affecting the evolution of the gamma parameters and the DSDs. Overall, I found the description of a unique set of data interesting and formative, and hence believe that the paper is worthy of publication. However, there are some

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issues that should be addressed in order to improve the presentation before the paper is published as discussed below.

(Answer) We would like to thank Anonymous Referee #3 for the invaluable comments. Below we address them individually as best we can.

1. (Comment) The authors segregate the flights that are flown into the different regions of the Amazon where they are flown. Although changes in surface conditions are no doubt important for affecting the cloud properties, meteorological conditions can also have an important impact on cloud properties. Some comments about this should be added to the manuscript and some analysis of the meteorology on the different days should be added to see if such differences can also explain some of the variation in cloud properties. I think attributing much of the changes to aerosols is not fully justified until the meteorological context is further explored.

1. (Answer) The meteorological context is clearly determinant for cloud formation over the Amazon or over any other region. We address this issue in two steps in the paper. Firstly, we show satellite images in Figure 2, clearly indicating the predominance of cumuli fields for all flights chosen. Flight AC07 deviates a little from this pattern, where deeper convection was observed. However, the aircraft pilot usually avoided penetrating deeper convection for safety reasons (at least in the lower levels). Therefore, even if there was deeper convection in the region, the aircraft actually penetrated the growing convective elements around it. Additionally, we show temperature and humidity profiles in Figure 4. Those profiles show that, even though the cumuli fields are relatively similar, there are some thermodynamic differences. Clouds over the Southern Amazon were subject to drier and warmer air, justifying their higher cloud base altitude. We do not believe that those differences would significantly impact the characteristics of the warm-phase DSDs. They may impact the overall lifecycle of the clouds and precipitation, but the microphysics in the lower parts of the clouds likely depend on factors such as updraft speed and, most importantly, aerosol concentration and size distribution. The effects of thermodynamics and aerosol properties on cloud microphysics

were studied in a precedent paper (same special issues - https://doi.org/10.5194/acp-17-10037-2017)

2. (Comment) I was a bit surprised on page 6 where the authors described that they were focusing on the CDP measurements where D < 50 micrometers. It would seem to me to be quite important to also examine the drizzle sized drops measured by the CIP, as when drizzle was present it would seem to be very important to account for that in the analysis. How are flights handled when there was some precipitation-sized drops? Were these larger drops incorporated into the analysis of simply ignored? Further, for Eq. (2) to Eq. (4) should the incomplete gamma function rather than the gamma function be used to account for the fact that not the complete size range of particles were measured?

2. (Answer) In this study, we are really interested in analyzing cloud droplet physics rather than drizzle/precipitation physics. Those are rather different. For instance, the condensational pseudo force is mostly insignificant for precipitation-sized liquid droplets. We indeed removed the drizzle/precipitation droplets from CIP for the Gamma fit, similarly to what models do. Models separate cloud and precipitation DSDs, that can be combined if need be. Another reason is that droplets with D > 50 μm were relatively infrequent in our measurements. In the warm phase, T > 0 °C, the number of data with LWC(D>50) > 0.1 g m-3 is only 8% of the cases where LWC(D<50) > 0.1 g m-3 (i.e. only a small portion of the data contained significant amounts of drizzle/precipitation). We added the following sentences to the second paragraph in Section 2.2: “The intent is to focus on cloud droplet growth processes and bringing the analysis closer to modeling scenarios. Additionally, the percentage of data with significant liquid water content (LWC) for D > 50 μm is relatively small. The number of data with LWC(D>50) > 0.1 g m-3 is only 8% of the number of DSDs with LWC(D<50) > 0.1 g m -3”.

Regarding the incomplete Gamma function, we reproduce our answer #4 for Anonymous Referee #4: “While we agree that the incomplete Gamma distribution would fit better the measurements, its use would result in other issues. As one of the main interests of the paper is to study the theoretical Gamma phase-space and its applicability to cloud modeling in the future, the use of the incomplete Gamma would not be ideal. In a modeling scenario, you don't have the observed DSD and therefore have no way of finding the truncation diameters. Additionally, the use of the incomplete Gamma distribution might add artificial patterns to the phase-space that are due to the truncation and not to physical processes".

3. (Comment) I think some more comments on the quality of the microphysical measurements are needed. How did the CAS and CDP probes compare? What are the estimated uncertainties in the size distributions? How did the LWC integrated from the CAS or CDP compare with bulk measurements from a hot-wire probe, which I am assuming were made. I am assuming that fits were only done to the liquid distributions, or do you use all the distributions? This should be clearly stated when discussing the phase partitioning at the bottom of page 8.

3. (Answer) The instruments uncertainty, as well as their intercomparison, is thoroughly analyzed in Braga et al. (2017) – same special issue (ACRIDICON-CHUVA). We updated the text with this reference (see second paragraph in Section 2.2). The fits were made to all measurements, irrespective of the NIXE-CAPS classification. However, this should not result in problems for our analysis given that the focus of the fits was primarily in the warm phase. Note that we do not draw any conclusions regarding the fits for regions above the transition between warm and mixed layers. We added the following sentence at the end on the NIXE-CAPS paragraph in page 8 to reflect this comment: "The NIXE-CAPS classification is a separate analysis and will not be considered as a filter to apply the Gamma fits to the CDP measurements. The CDP data fits are primarily focused on the warm phase and the transition to the mixed layer, where liquid droplets predominate".

4. (Comment) The implicit basis of the analysis presented in the Gamma phase space is that one is dealing with a Lagrangian case. But, inevitably, with any sort of microphysical measurements different samples of particle populations are being sampled.

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Further, there can be mixing and dynamic motions in clouds that would affect how the DSDs vary in the gamma phase space. Is there any way of representing these mixing processes on the diagram? I also think the action of the pseudo-forces and the impact of condensational growth and collision-coalescence could be better illustrated on the diagram. Can you show an example size distribution (it can be a theoretical rather than observed distribution if it is easier) and show how the size distribution would change due to simple model calculations of either condensational or collision-coalescence growth. Then, illustrate the location of all 3 DSDs (original, one undergoing condensational growth, and one undergoing collision-coalescence growth) on the gamma phase space and it will be easier for the reader to appreciate how these forces are represented on the diagram. Such simple theoretical/modeling calculations may also help you assess how the DSD characteristics are being affect by homogeneous/inhomogeneous mixing (discussion at top of page 12).

4. (Answer) As you correctly pointed out, it is impossible to produce Lagrangian trajectories based on aircraft microphysical measurements. Therefore, we have to make some assumptions to constrain our method. The flight patterns were specifically chosen in order to follow growing convective elements, where the aircraft penetrated the tops of the clouds. In this way, we both avoided precipitation from above and also tightened the relationship between the altitude of the measurements and the lifecycle of the clouds. We do not presume to claim that this guarantees that our trajectories are Lagrangian. In fact, when it comes to the observations, we never mention it. We just use the altitude of the measurements as a proxy for cloud evolution, meaning that higher measurements present "older" droplets. We believe this is rather reasonable and is also common place in microphysical studies. The confusion might come from the way we described the theory of the Gamma phase space in Section 2.3. In this idealized scenario, we can think of Lagrangian trajectories in order to facilitate the comprehension of the processes that affect DSD evolution. Now the link between the observations and the Lagrangian trajectories, for instance, should be addressed by other means such as modeling. As the title of the paper says, we illustrate the microphysical processes

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observed in the Gamma phase space rather than attempt to implement it in any actual modeling tool. This is the natural next step, of course, which is already ongoing. We added the following sentence in the second paragraph of Section 2.1 to further detail the flight patterns and why they could be used as a proxy for cloud evolution: “The latter step was deployed as follows. After the cloud base penetration, the aircraft performed several penetrations in vertical steps of several hundred meters. In each step, the aircraft penetrated the cloud tops available, thus avoiding precipitation from above. In this way, different clouds can be penetrated in the same altitude level, but the vertical steps followed the growing cumuli field overall”.

In order to compare the results in the paper to a Lagrangian case, we ran a simple model. Please refer to the answer #2 to Anonymous Referee #2. From those calculations, we were able to conclude two things. Firstly, that the qualitative results from the model agree well with our observations. Therefore, even though we could not produce Lagrangian observations, they agree with Lagrangian calculations. Secondly, we were able to test your suggestion regarding the actual calculations of the pseudo-forces (or at least displacements in the phase-space). We were able to confirm the overall directions of the pseudo-forces between the observations and the model, while also quantifying the displacements due to each growth process. The details of the model run can be found in the mentioned answer #2 to Anonymous Referee #2. We also added three new paragraphs to Section 2.3 commenting on the Lagrangian results. Additionally, the answer to Anonymous Referee #2 were also compiled in a new supplement. Regarding the effects of homogeneous or inhomogeneous mixing in the phase-space, we believe it is beyond the scope of this work – which is focused primarily on condensation and collision-coalescence. However, it shouldn’t be hard to analyze the effects on the phase-space. Note that there is significant literature regarding the effects of mixing on the DSDs. Therefore, one suggestion would be to apply the knowledge we have to a Gamma DSD and study the displacements in the phase-space.

5. (Comment) I’m wondering if some different terminology could be used to refer to

the different flights. Although referring to flight numbers (e.g., AC19, AC18, AC12, etc.) might be very informative for people who were involved in the field program, I continually had to refer back to the table to remember the regions in which the flights were conducted to help interpret the data. Can you refer to them as maybe AC1 (AC19 for Atlantic coast 1), RA1 and RA2 (AC09 and AC18) for remote Amazon, and AD1, AD2 and AD3 (for AC07, AC12, and AC13) so that it is more easy to remember the flights going through the manuscript. Or, maybe some other terminology would also work.

5. (Answer) Indeed, this would greatly facilitate reading the paper. We kept the ACXX nomenclature in Table 1 for consistency with the other special issue papers and added the new definitions as: 1) M1 (as in Maritime1 - AC1 might be confused with the ferry flight with the same nomenclature even though we don't mention it in our paper) for flight AC19; 2) RA1 and RA2 for AC09 and AC18 as you suggested; and 3) AD1, AD2, and AD3 also per your suggestion.

6. (Comment) With regards to the depiction of the DSDs in phase space, I would find it much easier is some 2-d cross sections were presented in addition to the 3-d volumes (it was hard to follow some of the discussion on the contrasts between clean and polluted trajectories). It is very hard to visualize how the different parameters are changing on these 3-d plots, so some 2-d cross sections would also offer some supplementary information. Further, what are the uncertainties or range of possible values in the gamma parameters.

6. (Answer) Thank you for this suggestion, we added the requested cross sections and it is much better now. With regards to the data spread around the trajectories, it can already be observed in Figures 5-7.

Minor Comments:

1. (Comment) Page 2, Line 20: I was surprised to see that the undisturbed portions of the rainforest are said to have homogeneous surface properties: compared to oceanic

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surfaces surely the nature of the forest is somewhat inhomogeneous? On page 5 (lines 20-25), the authors talk about differences in surface and thermodynamic conditions on more of the disturbed areas of the Amazon, so I found that this comment was a bit misleading.

1. (Answer) Surface conditions over the forest is indeed less homogeneous than over the ocean. The intended meaning is to say that it is more homogeneous than urbanized regions. The sentenced was changed to reflect this: "...Given the relative homogeneity of the surface (as compared to urbanized regions) and the pristine air over undisturbed portions of the rainforest..."

2. (Comment) Page 3, Line 1: Typically the term ice nucleating particles (INPs) rather than ice nuclei (IN) now. See Vali (2015).

2. (Answer) Agree, thanks.

3. (Comment) Page 4, line 9: Unless specific numeric values are quoted, the parameters of the gamma function (or any parameter in general) do not have units associated with them. They could be given in any unit with an appropriate conversion being made. Recommend removing the units in parenthesis.

3. (Answer) Added a clarification explaining that the units given are the ones to be considered in this study.

4. (Comment) Page 5, line 23: if the convective clouds were growing, how could you ensure that the third stage was always flown through the growing tops? It would seem that different altitudes below cloud top might have been sampled for the different population of clouds.

4. (Answer) The aircraft performed several steps in altitude and in each level the pilot looked for cloud tops available for penetration. There may be some differences regarding the distance to the cloud top, but the overall intent was to minimize precipitation falling from above as much as possible.

5. (Comment) Page 7, Eq. (7). I don't think this equation is correct (the factor of 10ËĘ-9). Any equation must be unit-independent. Constants for conversions between specific unit sets hence don't belong in equations as those factors will automatically appear when converting between the different units of the variables.

5. (Answer) We are sticking to the units we actually used. We provide them right after the equations, therefore it is easier for the reader to understand directly what we did. Added the following sentence before the equations for clarification: "In the units considered here, the equations are given by:".

6. (Comment) Page 8, line 4: If the fact epsilon obtained by the gamma parameters does not match those from the DSDs suggest that the gamma distribution does not give a good fit to the DSD?

6. (Answer) We mention that the Gamma-epsilon and the Observed-epsilon are tightly linked by eps_gamma = 0.95*eps_obs (R2 = 0.93). Therefore, it is safe to say that the observed epsilon is well represented by the Gamma fit. The Gamma DSD is only slightly narrower (angular coefficient of 0.95). Changed the sentence to: "The relative dispersion of the Gamma DSD may differ from the observations, given the differences between the parameterized and observed DSDs. However, our measurements show that the Gamma and observed ε are closely related by ε_Gamma=0.95ε_Observed (R2 = 0.93), showing that the Gamma DSDs are slightly narrower on average" for clarification.

7. (Comment) Page 9, line 12: Can you use a different word rather than "phase transitions?" there is some confuse about whether you are talking about phase space or the phase (liquid, mixed or ice) of the cloud particles.

7. (Answer) Changed to phase-state transition.

8. (Comment) Page 11, line 16: "from drier air", can you list the humidities in Table 1?

8. (Answer) The humidity for the different regions is shown in Figure 4.

9. (Comment) Page 11, line 23: Do you mean average RH? Clouds do not form in an environment where the relative humidity at their location is between 60% and 90%. Can you also give some indication of the thickness of the different cloud layers?

9. (Answer) Added “surrounding environment” instead of only “environment” for clarification. This is the air around the clouds and not within them. It is hard to provide cloud thickness because they are growing as the airplane ascends. However, they can reach altitudes up to 15 km approximately.

10. (Comment) Page 12, lines 13-14: How do you know the observations were obtained close to cloud top? Unless you have remote sensing data or some ascents out of cloud, is it conceivable the particular cloud you were sampling extended to a higher height?

10. (Answer) As explained previously, we can be relatively sure that the aircraft penetrated the cloud top by the flight pattern planning. The pilot looked for cloud tops in each flight level.

11. (Comment) Page 13, line 1: What is classified as a significant difference? Was some sort of statistical test applied?

11. (Answer) Sentence changed to “At first glance, it is possible to see stronger differences between the trajectories in the different regions, while internal variations are much weaker”.

12. (Comment) Page 14, line 12: What statistical test was applied to know that the res

12. (Answer) The text of this comment is cutout, so no changes were applied.

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