

Reference: ACP-2014-463 - Atmospheric Chemistry and Physics

Title: "“The biomass burning aerosol influence on precipitation over the Central Amazon: an observational study” "

Authors: Weber A. Gonçalves, Luiz A. T. Machado and Pierre-Emmanuel Kirstetter.

Dear NataschaTöpfer
Copernicus Publications
Editorial Support

Please find enclosed the new manuscript version and the author's response to the comments from the Referee #1 and Referee#2. We have addressed all comments and suggestions. We really appreciated the comments. New discussions and references were introduced in the text. We consider that this new version of the manuscript is more consistent and better confirm our major findings.

Below, please find a detailed response to the referee #1 as well as the changes in the manuscript.

Best Wishes,

Weber Gonçalves

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Title: "“The biomass burning aerosol influence on precipitation over the Central Amazon: an observational study” "

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Comments and answers to the Referee #1

Thank you for your careful review and comments to improve the quality of the manuscript. We really appreciated all yours relevant comments. All suggestions are commented bellow, the paper now is more complete and the main subject is better addressed.

I) Comments from Referees

1) The effect of aerosol absorption should be considered seriously as an important player. They briefly mention references considering the aerosol absorption effect in the data analysis part and never discuss it more. Aerosol absorption was shown in many studies to play an important role during the dry season. It can explain many of the results by simply suggest that when the conditions are more stable and cloud fraction is relatively low, the interaction of the smoke with EM radiation is larger and therefore warming by absorption can further stabilize the atmosphere. They can find many references for such process. The fact that there is a competition between microphysical and radiative effects is very important in the amazon. It'll change the papers interpretation.

2) The authors use the Manaus sounding measurements as a key part of the data. Therefore all results are gathered within +/- 2hrs around the measurements. This is a major problem of the analysis in my opinion. Manaus is 4 hrs after GMT. It means that all measurements are around 8am or 8pm. These times are probably the worst to study convection in the Amazon. I suspect that whatever is studied here might be the tail of the distribution. The Amazonian convection develops slowly from the morning and peaks in the afternoon. After the afternoon strong rain the whole atmosphere is getting more stable

3) In this article the statistic is based on observations of one El NINO year. Although it is based on a large number of rain observations the conclusions made about the difference between the wet and dry season are weak. In EL-NINO year we expect the rain characteristics in that area to be significantly different than the average. This again suggests that the study is on a very specific subset of the whole data.

4) The introduction is sparse. The authors do not use the known terminology for the aerosol effects and cite the wrong papers for the discussed effects. This is true for the entire paper. Parts that should be in the introduction appear in other places in a partial form. The paper should be reedited.

5) Abstract – there are many good reasons for understanding aerosol cloud interactions not only deforestation fires.

6) Specify better the months of the wet and dry season throughout the paper. I think that the use of the word “semester” here is strange.

7) P 5 L 20-26: I didn't understand why the explanation of the Z-R relation is important? The results afterwards are only based on Z and not R.

8) P 8 L 1: It is not clear what the described process is in this case. It could sound like the intensity of the rain increase due to the decrease in the RF. If so, why is it true?

(I) Author's Response

1) The manuscript now discusses the effect of aerosol absorption in several parts of the text introducing new references and clarifying this aspect. There is a competition effect between microphysics and radiative effect reducing precipitation, however, the quantification of each effect in the rainfall is not possible with this database. We also discuss the effect of the radiative effect during the unstable situation. In these situations the radiative effect does not seem to be predominant, as there is a significant amount of polluted periods with high CAPE values (Figure A), there are unstable cases for high black carbon concentration. The thermodynamics effect has a smaller time scale than the radiative effect and in the convective scale the instability acts faster increasing updrafts and developing a mesoscale circulation that maintain the cloud lifecycle.

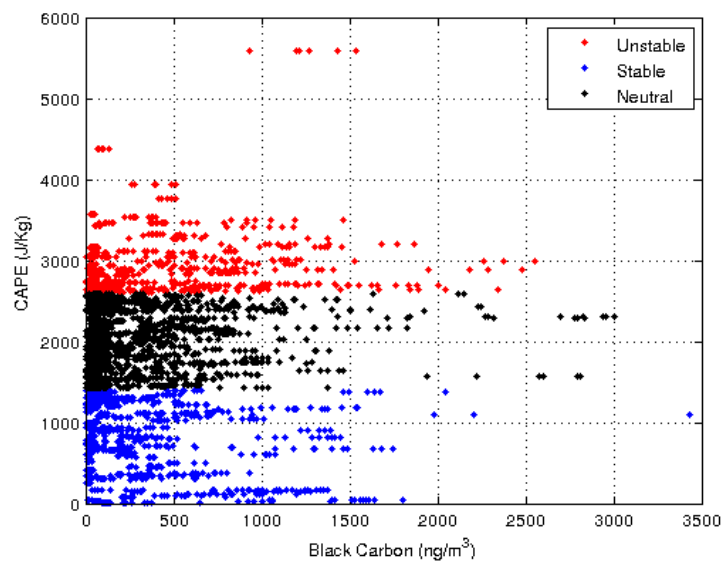


Fig. A. Scatter plot diagram for CAPE versus Black Carbon Concentrations for the entire year of 2009 collected by EUCAARI.

2) This is a question we had raised when we decided to evaluate the CAPE in this paper. We were expecting to have only very few large value of CAPE, but the detailed analysis of CAPE distributions showed this dataset appropriated to be used in this study. Actually, even at 8am we have a reasonable range of CAPE values (see the distribution in Fig. B). At 8pm the amount of higher values is larger (see Figure B). The more stable and unstable values are the tails of the distribution and these days corresponds to more extreme population of thermodynamics condition that we would like to evaluate. We do agree that convection in the Amazon peaks in the afternoon and soundings around noon would be more representative. Unfortunately, there is no historical dataset of sounding in Manaus in this period because it is regularly launched at synoptic time. In the future, with the GoAmazon campaign we will have, during specific period, 4 radiosondes per day and a specific correlation between sounding at 8am and 16am would be possible to be established.

Figure B presents histograms for the CAPE values used at 00 and 12 UTC in this research. It is

observed that the 00 UTC histogram presents an elevated occurrence of high CAPE values (>2600 J/kg). It is also noted that even less frequent, high CAPE values also occurs in the morning (12 UTC). This behavior could be explained by the fact that we observed from our soundings that more than 70% of the days which presented CAPE values higher than 2600 J/kg at 00 UTC high values were also identified in the next morning. We added this discussion in the text to highlight this feature.

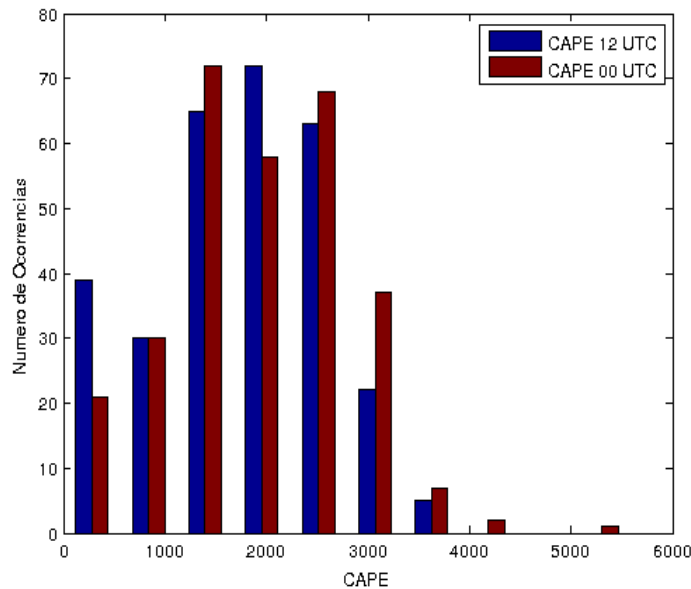


Figure B – CAPE histograms for 00 and 12 UTC in Manaus in 2009.

3) We do agree that convection in the Amazon is affected by El Niño configurations. Ropelewsky and Halbet (1987) and Peel et al. (2002) commented that the Amazon is one of the most important regions in the tropics where precipitation is influenced by El Niño occurrences. Ropelewski and Halbet (1987) commented that during El Niño periods, less precipitation is observed in the Amazon. However, less rainfall is not necessarily linked to weaker precipitating systems, but to the quantity of these systems. So, as the El Niño configuration was observed in the second semester of the year, the quantity of precipitating systems was probably inferior than in a regular dry season. Therefore, the El Niño effect acts to reduce the number of rainfall events and not the characteristics of the convective event. For the evaluation of stable and unstable atmosphere and the relationship between aerosol-rainfall we have enough cases to have statistical significance in our results. Also, for the study of size and aerosol loading, however, we agree that we had a non-significant number of rain cell lifecycle to study the effect of aerosol in the lifecycle duration. These points were clarified in the manuscript.

References for this question:

ROPELEWSKI, C. F.; HALBERT, M. S. Global and regional scale precipitation patterns

associated with El Niño/Southern Oscillation. *Monthly Weather Review*, v. 115, p. 1606-1626, 1987.

4) We changed the Introduction and several parts of the manuscript. We hope now have addressed the right references to the study.

5) Yes, we do agree that there are many other reasons for understanding the aerosol cloud interactions. Nevertheless, we just cited the deforestation fires because BBA predominates in the mean annual aerosol optical thickness in the Amazon, which is our study region. Also, because in this study we used black carbon, which is a byproduct of a partial combustion of fossil or wild fires, as an aerosol tracer. However, as the first sentence of the abstract is not clear that we focused on the Amazon region, this sentence was changed.

6) We do agree that the months of wet and dry seasons were not well specified in the paper. Then, we added a new sentence in Section 3, in order to clarify this aspect. We also agree that the word “semester” is not appropriate. Thus, this word was substituted for the word “season” and for the specific months throughout the text.

7) We agree that after the VPR explanation all results are based on Z, not in R. The explanation of the Z-R relation could lead to misinterpretations regarding to the data which we used. Then, in the actual version of the manuscript we eliminated the Z-R explanation. We have added more details from other important aspects related to the VPR technique. The text was modified.

8) We agree that this explanation is confusing in the manuscript. The results indicate that in the dry period, when the large scale precipitation decreases in the study area, most of precipitation in the area is related to intense convection. However, the increase of IRF is not due to the decrease of RF. The high IRF frequency observed is linked to the fact that most of intense convection occurs over elevated areas during the dry period, as shown in Fig. 2 in the manuscript. The sentence was modified in the manuscript.

(III) Author's Changes in Manuscript

1) Bellow some paragraphs discussing this subject in the manuscript:

“Two main effects are well documented: radiative or direct, and microphysical or indirect. The first effect is related to the BBA high capacity of absorption in the visible portion of the electromagnetic

spectrum (Ramanathan et al. 2001, Wake, 2012). This absorption could warm the atmosphere (Koren et al., 2004; Randles and Ramaswamy, 2010; Koch and Del Genio, 2010; Jacobson, 2014) and produce atmospheric stabilization (Koren et al. 2008). The indirect or microphysical effect is linked to the possibility of BBA particles becoming cloud condensation nuclei (Roberts et al. 2001). As a result, it is expected that the amount of cloud droplets would increase with the particle concentration (Rosenfeld, 1999; Ramanathan et al., 2001; Nober et al., 2003; Andreae et al., 2004; Qian et al., 2009).”

“One of the most important issues regarding the aerosol-cloud interactions is the determination of the predominant effect, radiative or microphysical. In warm rain suppression, both effects seem to act together. However, quantifying their respective contribution is still an important issue. Warm rain suppression evidence was firstly documented by Rosenfeld (1999), and then similar results were also obtained and presented in the literature by Nober et al., (2003), Koren et al., (2004) and Qian et al., (2009). The suggested indirect effect mechanism for warm rain suppression is related to the fact that BBA could act as cloud condensation nuclei. A high concentration of small cloud droplets occurs in polluted environments (Rosenfeld, 1999; Ramanathan et al., 2001; Nober et al., 2003; Andreae et al., 2004; Qian et al., 2009), which compromises the coalescence process (Kaufman et al., 2005). These droplets do not reach the required size in order to precipitate and can rapidly evaporate (Artaxo et al., 2006).”

“The radiative effect that acts to stabilize the atmosphere is of a second order because even with high BBA the atmosphere is highly unstable, and thermodynamics, on this time scale, dominates over the radiative process. Also, the feedback effect due to the radiative effect, which increases droplet evaporation, does not seem to be the predominant mechanism. Probably, the high instability (high updraft) and the large number of droplets inside the cloud ascend very fast, thereby reducing the evaporation. Although impossible to quantify, the wet scavenging also seems to be of second order, and would act in the opposite direction through the fact that precipitation did not decrease BC concentration at any point of the curve (Fig. 4b). During the dry season only the upslope regions trigger convection and in the highly unstable cases it appears that BBA helps to increase ice nucleus, increasing precipitation.”

“This could be associated to the warm rain suppression mechanism or the direct radiative effect, or an association of the radiative and microphysical effects together. During the dry season in an unstable atmosphere, the convective invigoration for elevated concentrations of BBA seems to be a very significant result, because all other features act to reduce precipitation in polluted atmospheres, such as wet scavenging. The probable physical mechanism is related to stronger updrafts inside the rain cells initiated over upslope regions, which could increase ice nucleus and strengthen convection. It is true that the vertical velocity within the precipitating systems was not available in the database used.”

2) Below the paragraph discussing this subject in the manuscript:

“Atmospheric soundings, which were collected twice a day, at 00 and 12 UTC. The atmospheric soundings were used to calculate the Convective Available Potential Energy (CAPE), an important atmospheric index used as an intense convective activity predictor (Wallace and Hobs, 2006). As

Manaus radiosondes were released by an operational station, only soundings at 00 and 12 UTC, 08 and 20 local time, were available. The best time for a sounding in this study would be sometime around noon when convection starts to develop. However, the CAPE dataset was evaluated and shown to have very useful information and capture the daily instability feature even though it was not recorded at the most appropriate time. In an evaluation of the sounding dataset we observed at 00 UTC a considerable population of high CAPE values, but less frequently than at 12 UTC.”

3) Below the paragraph discussing this subject in the manuscript:

“The El Niño configuration, as was observed during the dry season, is associated to less precipitation due to a decrease in the occurrence of rain cells. Even if this situation decreases the rain cell population in order to study the lifetime duration, a significant number of samples were analyzed for the evaluation of the aerosol-rainfall interaction, and this did not compromise the main results of this study that are associated to the convective scale.”

4) Following is the new introduction of the manuscript.

“Every year the Amazon Forest faces a large amount of aerosol from pasture and forest fires, and the pollution plumes generated can spread over large areas (Martin et al., 2010). The Amazon Biomass Burning Aerosol (BBA) alters the atmospheric particulate material composition (Ryu et al., 2007) and can influence cloud formation, precipitation and the radiation budget (Artaxo et al., 2002; Lin et al., 2006; Tao et al., 2012; Camponogara et al., 2014). Accordingly to Tegen et al. (1997), BBA predominates in the mean annual aerosol optical thickness in the Amazon. The dry season, which occurs between July and December, is the period that faces greater biomass burning emissions (Artaxo et al., 2002; Altaratz et al., 2010; Martin et al., 2010; Camponogara et al., 2014). However, from January to June (wet period), BBA is also observed in the Amazon Basin (Martin et al., 2010).

In recent years, the scientific community has made great efforts to understand the effect of aerosols on cloud and precipitation in order to reduce uncertainties in climate prediction (Tao et al., 2012). Two main effects are well documented: radiative or direct, and microphysical or indirect. The first effect is related to the BBA high capacity of absorption in the visible portion of the electromagnetic spectrum (Ramanathan et al. 2001, Wake, 2012). This absorption could warm the atmosphere (Koren et al., 2004; Randles and Ramaswamy, 2010; Koch and Del Genio, 2010; Jacobson, 2014) and produce atmospheric stabilization (Koren et al. 2008). The indirect or microphysical effect is linked to the possibility of BBA particles becoming cloud condensation nuclei (Roberts et al. 2001). As a result, it is expected that the amount of cloud droplets would increase with the particle concentration (Rosenfeld, 1999; Ramanathan et al., 2001; Nuber et al., 2003; Andreae et al., 2004; Qian et al., 2009).

One of the most important issues regarding the aerosol-cloud interactions is the determination of the

predominant effect, radiative or microphysical. In warm rain suppression, both effects seem to act together. However, quantifying their respective contribution is still an important issue. Warm rain suppression evidence was firstly documented by Rosenfeld (1999), and then similar results were also obtained and presented in the literature by Nober et al., (2003), Koren et al., (2004) and Qian et al., (2009). The suggested indirect effect mechanism for warm rain suppression is related to the fact that BBA could act as cloud condensation nuclei. A high concentration of small cloud droplets occurs in polluted environments (Rosenfeld, 1999; Ramanathan et al., 2001; Nober et al., 2003; Andreae et al., 2004; Qian et al., 2009), which compromises the coalescence process (Kaufman et al., 2005). These droplets do not reach the required size in order to precipitate and can rapidly evaporate (Artaxo et al., 2006).

Based on the observations of warm rain suppression over regions with forest fires, Diehl et al. (2007) suggested that the ice phase could be an important factor in the rain process. In fact, laboratory measurements indicate the high capacity of ice nucleation by BBA (Petters et al., 2009). In recent years, some studies have suggested that ice phase clouds are invigorated by the presence of aerosols from vegetation fires (Andreae et al., 2004; Lin et al., 2006; Rosenfeld et al., 2008; Altaratz et al., 2010; Koren et al., 2012; Storer and Heever, 2013). Rosenfeld et al. (2008) propose a conceptual model based on the effect of aerosols on deep convective cells, which is mainly associated to the microphysical effect. Accordingly to the authors, due to the high concentration of aerosols in polluted environments, the raindrop nucleation process would be slower than in unpolluted areas. Besides, in atmospheres which favor deep convective activity, these droplets and aerosols could ascend into the atmosphere, reaching the frozen layer, acting as ice nuclei and releasing more latent heat, which in turn increase the updrafts and strength convection (Lin et al. 2006; Rosenfeld et al. 2008). Over a certain time, the cloud accumulates higher liquid water and ice contents, favoring more intense rainfall rates and increasing electrical activity (Graf, 2004). However, even with this evidence, the cloud invigoration process by aerosols still needs to be better understood (Altaratz et al., 2014).

Although well documented, especially in recent years, the BBA effect on clouds and precipitation is still a source of debate in the scientific community. One of the most important issues is related to filtering the aerosol-precipitation relationship from other dominant atmospheric components. In order to reach this goal, this study presents a new methodology which is based on the atmospheric degree of instability. The possibility of using ground based measurements has the potential to contribute to the present scientific knowledge of the BBA influence on precipitating cells in the Amazon region. Rain, ice content, size and duration of precipitating systems retrieved from a S-band radar were evaluated as function of black carbon concentration over the largest Amazon City

(Manaus, Amazonas state, Brazil).”

5) “Understanding the influence of biomass burning aerosols on clouds and precipitation in the Amazon is an important key in order to reduce uncertainties in simulations of climate change scenarios with regards to deforestation fires.”

6) Explanation of the rainy and dry periods in Section 3:

“The Manaus precipitation characteristics were obtained from the calculation RF and IRF. The RF and IRF were normalized by their annual mean and standard deviation in order to compare both annual cycles. The result (Fig. 1a) was useful in determining two distinct periods to perform the analysis. Months during which the normalized RF was greater/smaller than zero were considered rainy/dry seasons. Then, the period of the year between January and June was considered the rainy season and the months from July to December, the dry season.”

- Sentences which the word “semester” was substituted throughout the manuscript

“The most important results were obtained during the dry season (July-December).”

“The dry season, which occurs between July and December, is the period that faces greater biomass burning emissions (Artaxo et al., 2002; Altaratz et al., 2010; Martin et al., 2010; Camponogara et al., 2014).”

“However, from January to June (wet period), BBA is also observed in the Amazon Basin (Martin et al., 2010).”

“In other words, even with a high peak of reflectivity being observed over elevated regions, during the rainy season precipitation occurs nearly homogeneously.”

“This characteristic observed during the dry season lead us to try filtering the possible aerosol influence on precipitation from an atmospheric feature in which could modulate the effect.”

7) “The S-band radar data were processed following the TRADHy strategy (Delrieu et al. 2009), briefly described hereafter. A preliminary quality control of the radar data was performed, and the radar calibration was checked throughout the year of 2009. The area actually sampled by the radar was determined for each elevation angle with characterizing partial or complete beam blockage and ground clutters. Rain types and the corresponding vertical profiles of reflectivity (VPR) were

dynamically identified. Regarding the VPR identification, the initial method used in TRADHy performs a numerical identification of the VPR from the comparison of the radar data at different distances and altitudes to account for sampling effects (Kirstetter et al., 2010). In the present study the physically-based approach described by Kirstetter et al. (2013) was used for enhanced robustness to identify a representative VPR over the radar domain for a given precipitation type. Corrections for both clutter and beam blockage were performed along with a projection of measured reflectivities onto the ground level using rain-typed VPRs. At a given pixel, reflectivities from all available elevation angles were used for the projection. The projected radar reflectivity to a constant altitude plan at the same elevation as the radar was called the Constant Altitude Plan Position Indicator-Ground (CAPPI-Ground). The Vertical Ice Content (VIC) for each pixel of the radar images was also calculated. The method described in Kirstetter et al. (2013) is based on a modeling of the physical properties of the hydrometeors (size distribution, shape, phase, electromagnetic properties, etc.) contributing to the VPR features. In particular the model for the ice phase above the freezing level allows for the computation of the Vertical Ice Content (VIC). The identified VPR is then associated to a model for the ice phase, which is used to compute the VIC at each pixel alongside the projection of reflectivity at the surface.”

8) “This result indicates that in the dry period, when large scale precipitation decreases in the study area, most of the precipitation is linked to intense convection, which mainly occurs over elevated areas.”

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Title: "“The biomass burning aerosol influence on precipitation over the Central Amazon: an observational study” "

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Comments and answers to the Referee #2

Thank you for your careful reviews and comments to improve the quality of the manuscript. We really appreciated all yours relevant comments. All suggestions are commented bellow, the paper now is more complete and the main subject is better addressed. Besides, the manuscript was revised by a professional language editor.

(I) Comments from Referee

- 1) Page 18880, line 8: “instability degree” should be “degree of instability”. Note that this type of poor language discussion was observed throughout the paper, which made it very difficult to understand the significance of the results.
- 2) Page 18880, line 14-15: “investigation” would be more appropriate than “clarification”
- 3) Page 18881, line 9: Which aerosols act as CCN? The BBA? Please be specific
- 4) Page 18881, line 9: “high concentration” would be more appropriate than “great formation”
- 5) Page 18881, line 11: Doesn’t polluted environments impact the collision and coalescence process limiting the ability to form precipitation size particles?
- 6) Page 18881, line 14, “observations” instead of “evidences”
- 7) Page 18881, line 15-16: What do the authors mean be essential factor? Do you mean this is the primary mechanism for precipitation generation during high BBA conditions? If so, please clarify
- 8) Page 18881, line 18: “convective, ice phase clouds”
- 9) Page 18881, line 26: “content”
- 10) Page 18881, line 28: “understanding” would be more appropriate than “clarifications”
- 11) Page 18882, lines 1-7: This discussion is not coherent. It seems like the authors want to explain that the study will focus on understanding the relationship be between BBA variability in the Amazon and physical attributes (size, duration, etc.) precipitating cells This needs to be rewritten to provide a better understanding of the goals of the study
- 12) Page 18882, lines 20-21: Please be specific on what the MAAP instrument measures
- 13) Page 18882, line 27:”ice nucleation impacts on the cloud . . .”
- 14) Page 18883, line 4: “. . .CCN in mixed phased clouds have been shown to correspond to BC concentrations?”

- 15) Page 18883, line 10: What do you mean by “international negotiations”?
- 16) Page 18883, lines 11-28: a) The description of the radar data is very poorly written and very confusing. Details are as follows: b) What is detection domain? Is it a sampling area? c) What is characterizing screening effects? Is it beam blocked sectors? d) What is clutter? Is it ground clutter? e) What is identifications? Do you mean investigations? f) Why mention that you didn't use the initial VPR if you used the physically based method by Kirstetter et al. (2013)? If you mention the original VPR method, it must be described. g) What is the reflectivity data extrapolated to a CAPPI on the surface? This radar processing discussion needs significant amount of clarification
- 17) Page 18883, line 29: How is VIC calculated? It was not defined in the paper
- 18) Page 18885, line 3: “temporal sampling frequency” sounds more descriptive than “same sampling time”
- 19) Page 18885, lines 9-10: This sentence is very confusing. Do the authors mean that the high frequency sampling of the EUCARRI datasets provides adequate observations for the study?
- 20) Page 18885, line 17: How were RF and IRF normalized? Please define
The RF and IRF were normalized by their annual mean and standard deviation in order to compare both annual cycles.
- 21) Page 18885, lines 25-26: Doesn't the “frequency” of intense precipitation increase?
Yes, the word frequency was added to the manuscript.
- 22) Page 18886, lines 1-2: This sentence doesn't make sense. Do the observations indicate that as the large scale precipitation decreases in area, the convective intensity increases?
- 23) Page 18886, lines 3-14: An elevation rise of 160 m seems very small to generate significant orographic precipitation. Are the authors positive this increase in reflectivity over this terrain feature is not an enhancement due to ground clutter? The authors need to demonstrate that this is an enhancement of convective activity. How far is the feature from the radar? Please provide more detail
- 24) Page 18887, lines 1-13: This discussion is poorly formulated. Please just state the test. As mentioned before, the impact of terrain needs to be further explored
- 25) Page 18888: lines 6-8: What do the authors mean by this statement? Suppression of stratiform and convective rain occurs in stable conditions?
- 26) Page 18888, line 13: “grow” is better than “grow up”
- 27) Page 18888, lines 20-29 to pages 18889, lines 1-5: This discussion is not coherent. What test was applied? What opposite affect exists? What do you mean by punctual? Did this test exclude all precipitation that was observed over the EUCAARI site? If so, why? This discussion needs to be written to understand the test and outcomes of the testing of this hypothesis
- 28) Page 18889, line 8: what does “spread out” mean? Does it mean increase in a real extent?
- 29) Page 18889, line 17: What does “stretching” mean?
- 30) Page 18889, line 22: How was IF index calculated?

31) Page 18890, lines 14-19: This discussion of duration analyses is very confusing. Why was it inclusive? Are the authors trying convey that cells inside the study area provide no useful information, but all cells, except for merger and splits, provide interesting statistics? If so, please explain why?

32) Page 18891: lines 25-26: Couldn't the increase in rain cell sizes be a coincidence even though there positive relationship with increase in BC? This relationship needs to be investigated further even though the results are statistically significant

33) Page 18891, lines 16-18: What does “. . .throughout theoretical simulations which are not completely parameterized” mean?

34) Page 18891, line 20: “stratification” seems more appropriate than “component”

35) In Figs 4 and 5, the change in RF and IF for different BC concentration is very small (~1 % or less). Are these changes meaningful? Does that represent an observable difference that could be physically observed?

(II) Author's Response

1) The change was made in the entire manuscript, which went through an English review by a specialist.

2) The word was changed.

3) The word “aerosol” was changed to “BBA”

4) We agree, the change was made.

5) Yes, this behavior associated to the capacity of warming the atmosphere by BBA is responsible for the decreasing the formation of precipitation size particles, in warm clouds case.

6) The word was changed.

7) By the results found in the literature, and also in this manuscript, it is not possible to state that the ice phase is an essential factor in the aerosol-precipitation relationship. However, the ice phase is one of the important factors. So, we agree that the sentence should be modified for a better understanding. Following is the new sentence...

8) The change was made.

9) The word was corrected

10) We agree, the change was made.

11) We agree that this discussion is not coherent in the manuscript. So, this discussion was modified.

12) The Section 2 was rearranged for a better understanding. The MAAP instrument measures BC

concentrations every minute, making 30 minutes averages, which was used in this research.

13) The text was modified for a better understanding.

14) No, part of the CCN found in mixed phased clouds corresponds to BC concentrations. This phrase is in the manuscript to highlight the importance of BC concentrations regarding to nucleation and also to give support to the use of it as an aerosol tracer. However, we do agree that the sentence is not clear and it was modified.

15) This sentence was removed from the manuscript

16)

a) The radar data processing has been rewritten for a better clarification.

b) The detection domain of the radar is the area actually sampled by the radar, which is constrained by both the surrounding relief and vertical structure of precipitation. Ground clutters and beam blockage limit the detection domain. The vertical extent and heterogeneity of precipitation have also an impact, e.g. shallow precipitation can remain undetected if below the radar beam.

c) Partial or complete beam blockage characterizes screening effects. It is evaluated for each elevation angle.

d)Correct. It was corrected in the document.

e)Identification techniques are implemented to dynamically determine ground clutter and rain type as well as the corresponding vertical profiles of reflectivity.

f)The methods proposed to identify the VPR can be classified into four categories: (i) the direct estimation of the VPR from measured volume reflectivity data (e.g., Germann and Joss 2002), (ii) the numerical identification of the VPR from the comparison of the radar data at different distances and altitudes to account for sampling effects (Andrieu and Creutin 1995; Andrieu et al. 1995; Vignal et al. 1999; Borga et al. 2000; Seo et al. 2000; Kirstetter et al. 2010), (iii) the synthesis of the VPR with a few parameters (Kitchen et al. 1994; Tabary 2007) and (iv) the physically-based identification where models of vertical profiles are fitted to the radar observations (Kirstetter et al. 2013).

The TRADHy strategy described by Delrieu et al. (2009) involves the method proposed by Kirstetter et al. (2010), which falls in the second category. TRADHy was modified in the present study to accommodate the approach described in Kirstetter et al. (2013).

In fact the above-mentioned VPR identification methods are not always able to cope with VPRs temporal and spatial fluctuations. For example, Kirstetter et al. (2010) showed the improvement gained by filtering the beam-sampling effects in the VPR estimation relative to an apparent VPR directly derived from measured reflectivity data and differently affected by the range influence. A difficult radar measurement context (mountainous areas) shows the limits of the VPR identification used within the TRADHy software (Delrieu et al. 2009). A statistical control is applied on the variations of the VPR components about their a priori values. In case of strong or noisy fluctuations in the observations, the statistical control of the variations of the VPR components about their a priori values through a matrix of covariance (Vignal et al. 1999; Kirstetter et al. 2010) may be not robust enough to prevent getting physically unrealistic VPRs.

In order to enhance the robustness of the method and the physical realism of the retrieved VPR, the method in Kirstetter et al. (2013) bases on a modeling of the physical properties of the

hydrometeors (size distribution, shape, phase, electromagnetic properties, etc.) contributing to the VPR features. The VPR is identified from the comparison of the radar data at different distances and altitudes to account for sampling effects. A rain-typing algorithm is used for an a priori separation of convective and stratiform regions within the rain field (Delrieu et al. 2009).

g) For each radar pixel, the VPR is used to project measured reflectivities onto the ground level. This reflectivity field can be seen as a CAPPI at the ground level.

References for this question

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17) A description of VIC calculation was added to the manuscript.

18) The change was made in the manuscript.

19) Yes, but in this sentence we just intended to clarify that we used BC concentrations in the closest time to the radar data. As this sentence was confusing, it was modified and simplified.

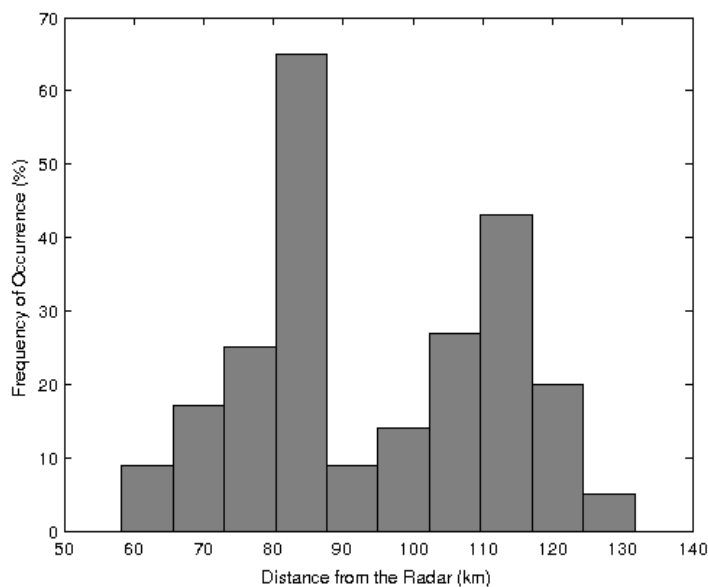
20) The RF and IRF were normalized by their annual mean and standard deviation in order to compare both annual cycles.

21) Yes, the word frequency was added to the manuscript.

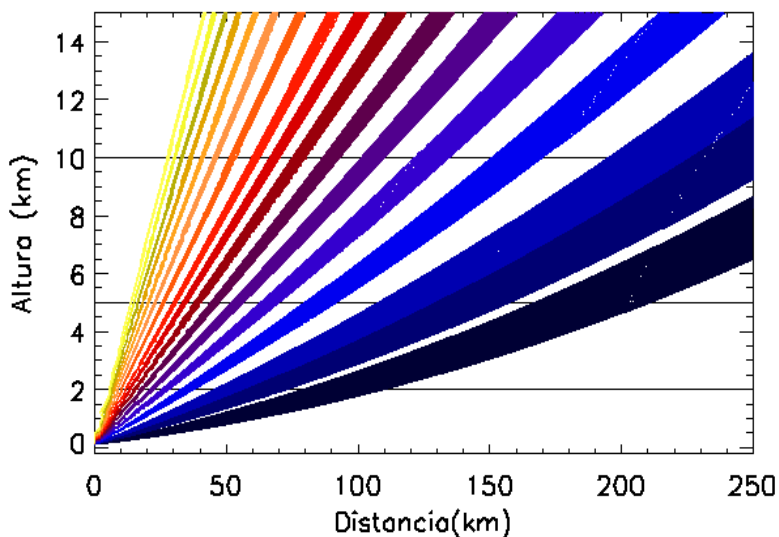
22) We agree that this explanation is confusing in the manuscript. The results indicate that in the

dry period, when the large scale precipitation decreases in the study area, most of precipitation in the area is related to intense convection. However, the increase of IRF is not due to the decrease of RF. The high IRF frequency observed is linked to the fact that most of intense convection occurs over elevated areas during the dry period, as shown in Fig. 2 in the manuscript. The sentence was modified in the manuscript.

23) We agree that an elevation rise of 160 m seems small to generate precipitation. However, Laurent et al. (2002) showed that the initiation of Convective Systems over the Amazon can occur even over smaller elevations (around 100 m). We generated a histogram (Figure Ca) of the distances from the radar for the last two terrain elevation bins, centered in 138 and 162 m. Then, the statistics are linked to elevations greater than 126 meters. These two bins are exactly those which presented peaks of reflectivity around 30 dBZ in the dry period. It can be noted that the closest “relatively high” elevation (>126 meters) is around 60 km distant from the radar. At this distance, the lower radar elevation band is around 1 km high (Figure Cb). This behavior eliminates the possibility that the peaks of reflectivity over terrain elevations greater than 126 meters are due to ground clutter. However, we agree that this discussion is very important and it was added to the manuscript.



(a)



(b)

Figure C – (a) Frequency histogram of distance from the radar of elevations greater than 126 meters; (b) Cross section of the volumetric scan strategy for the S-band Radar in Manaus. Each colored band represents one of the 17 elevations.

Reference to this question:

LAURENT, H.; MACHADO, L. A. T.; MORALES, C. A.; DURIEUX, L. Characteristics of the Amazonian mesoscale convective systems observed from satellite and radar during the WETAMC/LBA experiment. *Journal of Geophysical Research*, v. 107, n. 20, 2002.

24) This test was performed in order to verify if the topography influence on precipitation in the study domain would lead to misinterpretations regarding to the aerosol-precipitation relationship. However, we do agree that the text should be modified for a better understanding. We also changed the position of this test explanation in the manuscript. For a better interpretation, the description will be collocated after the results regarding to RF and BC concentrations

25) Strong convection is not likely to happen in stable atmospheres. We expect that just shallow clouds to form in this conditions. Then, the decrease of RF observed for high BC concentrations in the wet period probably are related to warm and stratiform clouds.

26) The change was made in the manuscript.

27) This discussion was modified in to facilitate the understanding.

28) Yes. However, this sentence was changed for a better understanding. The sentence was modified.

29) We used this term in order to clarify that high CAPE values are linked to stronger updrafts, then, related to the severity of the convection. However, the sentence was modified for a better understanding.

30) The text was modified.

31) The analysis regarding to the precipitating cells duration was inconclusive due to the fact that the calculation of life cycle duration is based in the detection of the rain cell in a sequence of radar images. Therefore the total number of rain cell is much larger than the number of life cycles of the rain cells. Also, when we considered just systems which have not slip or merge during their life cycle, there is a considerable reduction on the life cycles. This reduction did not lead us to divide the analyses in the same BC concentration categories as we did for the entire article, and the results were not statistically significant. As we were trying to understand the relationship between the cells duration and BC concentration in the radar domain, the analyzed systems could not be result of merge or split. When a precipitating system merge with another system, for example, the individual physical characteristics of each cell are modified. In this case, the result system could be stronger or weaker the previous, affecting its duration. This modification probably is not related to pollution, but to dynamics of the systems. The same behavior could happen with split systems. We agree that this discussion should be in the manuscript.

32) Based on the previous results showed in this research, where we found a convective invigoration in polluted and unstable atmospheres, the rain cell sizes increase do not seem to be a coincidence. The convective invigoration is probably due to stronger updrafts inside the rain cells, which transport aerosols and cloud droplets to the freezing level. These droplets and aerosols could act as

ice nuclei and after the freezing process release more latent heat, which in turn increase the updrafts and strength convection. So, the dynamic and thermodynamic involved in the convective invigoration process gives support to the development of bigger rain cells. Then, the results do not seem to be a coincidence, but have a physical connection between them.

33) At this point, we are trying to explain that that filtering the aerosol effect from other atmospheric features is very difficult throughout observational data. This issue could be better faced in modeling studies. However, as the aerosol effect is still a source of debate as its effect on precipitation still need more clarifications, the models are not completely prepared to simulate this relationship.

34) We preferred to add the word “filtering” before component, resulting in “filtering component”.

35) We agree that the mean RF and IF differences observed in Figures 4 and 5 are around 1%. However, the frequency histograms (Figures 4 and 5 c/d) were constructed to verify if these means were significantly different. We concluded that the first and third curves are significantly different at 95% by t test. The tail of the distributions varies from lower to higher BC concentrations, for both, stable and unstable conditions.

(III) Author's Changes

1) “The results indicate that the aerosol influence on precipitating systems is modulated by the atmospheric degree of instability.”

2) “However, due to the limitation imposed by the dataset used, certain important features such as the clarification of importance of each mechanism in the rainfall suppression need further investigation.”

3) “The suggested indirect effect mechanism for warm rain suppression is related to the fact that BBA could act as cloud condensation nuclei.”

4) “A high concentration of small cloud droplets occurs in polluted environments (Rosenfeld, 1999; Ramanathan et al., 2001; Nober et al., 2003; Andreae et al., 2004; Qian et al., 2009), which compromises the coalescence process (Kaufman et al., 2005). These droplets do not reach the required size in order to precipitate and can rapidly evaporate (Artaxo et al., 2006).”

5) “The suggested indirect effect mechanism for warm rain suppression is related to the fact that BBA could act as cloud condensation nuclei. A high concentration of small cloud droplets occurs in polluted environments (Rosenfeld, 1999; Ramanathan et al., 2001; Nober et al., 2003; Andreae et al., 2004; Qian et al., 2009), which compromises the coalescence process (Kaufman et al., 2005). These droplets do not reach the required size in order to precipitate and can rapidly evaporate (Artaxo et al., 2006).”

6) “Based on the observations of warm rain suppression over regions with forest fires, Diehl et al. (2007) suggested that the ice phase could be an important factor in the rain process.”

7) “Based on the observations of warm rain suppression over regions with forest fires, Diehl et al. (2007) suggested that the ice phase could be an important factor in the rain process.”

8) “In recent years, some studies have suggested that ice phase clouds are invigorated by the presence of aerosols from vegetation fires (Andreae et al., 2004; Lin et al., 2006; Rosenfeld et al.,

2008; Altaratz et al., 2010; Koren et al., 2012; Storer and Heever, 2013).”

9) “Over a certain time, the cloud accumulates higher liquid water and ice contents, favoring more intense rainfall rates and increasing electrical activity (Graf, 2004).”

10) “However, even with this evidence, the cloud invigoration process by aerosols still needs to be better understood (Altaratz et al., 2014).”

11) “Although well documented, especially in recent years, the BBA effect on clouds and precipitation is still a source of debate in the scientific community. One of the most important issues is related to filtering the aerosol-precipitation relationship from other dominant atmospheric components. In order to reach this goal, this study presents a new methodology which is based on the atmospheric degree of instability. The possibility of using ground based measurements has the potential to contribute to the present scientific knowledge of the BBA influence on precipitating cells in the Amazon region. Rain, ice content, size and duration of precipitating systems retrieved from a S-band radar were evaluated as function of black carbon concentration over the largest Amazon City (Manaus, Amazonas state, Brazil).”

12) “Black Carbon (BC) concentrations from the experiment European Integrated Project on Aerosol Cloud Climate and Air Quality Interactions (EUCAARI), with a sampling time of 1 min and averages every 30 min. The EUCAARI experiment used the Multi-Angle Absorption Photometer (MAAP) instrument (Slowik et al., 2007) and collected data 50 km away from Manaus city. The BC concentrations were used in the study as an aerosol tracer;”

13) “In addition, BC has received attention by the scientific community due to its potential for ice nucleation, which would affect the cloud microphysical properties (Cattani et al., 2006; Cozic et al., 2008). The supersaturation required for ice formation decreases with the presence of BC (DeMott et al., 1999). Cozic et al. (2007) found that a portion of the cloud droplet nuclei presented in mixed phase clouds are BC. Therefore, due to its potential for ice nucleation, the presence of BC would favor the development of ice phase clouds, including deep convection. Another important aspect related to BC particles is their capacity to absorb radiation in the visible portion of the electromagnetic spectrum (Ramanathan et al., 2001; Storelvmo, 2012; Tiwari et al., 2013; Ahmed et al., 2014). This characteristic could warm the layer where BC is present (Myhre, 2009; Mahowald, 2011; Jones et al., 2011; Wake, 2012; Wang, 2013), which in turn could also affect the cloud properties and precipitation.”

14) “Cozic et al. (2007) found that a portion of the cloud droplet nuclei presented in mixed phase clouds are BC.”

15) This sentence was removed from the manuscript

16)

a) “The S-band radar data were processed following the TRADHy strategy (Delrieu et al. 2009), briefly described hereafter. A preliminary quality control of the radar data was performed, and the radar calibration was checked throughout the year of 2009. The area actually sampled by the radar was determined for each elevation angle with characterizing partial or complete beam blockage and ground clutters. Rain types and the corresponding vertical profiles of reflectivity (VPR) were dynamically identified. Regarding the VPR identification, the initial method used in TRADHy performs a numerical identification of the VPR from the comparison of the radar data at different distances and altitudes to account for sampling effects (Kirstetter et al., 2010). In the present study the physically-based approach described by Kirstetter et al. (2013) was used for enhanced robustness to identify a representative VPR over the radar domain for a given precipitation type.

Corrections for both clutter and beam blockage were performed along with a projection of measured reflectivities onto the ground level using rain-typed VPRs. At a given pixel, reflectivities from all available elevation angles were used for the projection. The projected radar reflectivity to a constant altitude plan at the same elevation as the radar was called the Constant Altitude Plan Position Indicator-Ground (CAPPI-Ground). The Vertical Ice Content (VIC) for each pixel of the radar images was also calculated. The method described in Kirstetter et al. (2013) is based on a modeling of the physical properties of the hydrometeors (size distribution, shape, phase, electromagnetic properties, etc.) contributing to the VPR features. In particular the model for the ice phase above the freezing level allows for the computation of the Vertical Ice Content (VIC). The identified VPR is then associated to a model for the ice phase, which is used to compute the VIC at each pixel alongside the projection of reflectivity at the surface.”

b) No changes in the manuscript.

c) No changes in the manuscript.

d) “The area actually sampled by the radar was determined for each elevation angle with characterizing partial or complete beam blockage and ground clutters.”

e) No changes in the manuscript.

f) No changes in the manuscript.

g) No changes in the manuscript.

17) “The Vertical Ice Content (VIC) for each pixel of the radar images was also calculated. The method described in Kirstetter et al. (2013) is based on a modeling of the physical properties of the hydrometeors (size distribution, shape, phase, electromagnetic properties, etc.) contributing to the VPR features. In particular the model for the ice phase above the freezing level allows for the computation of the Vertical Ice Content (VIC). The identified VPR is then associated to a model for the ice phase, which is used to compute the VIC at each pixel alongside the projection of reflectivity at the surface.”

18) “As presented previously, the datasets did not have the same temporal sampling frequency.”

19) “The BC concentrations, from the EUCAARI measurements, used were those which had the closest sampling time to the radar data. These considerations allowed us to combine the variables described in order to understand the aerosol effect on precipitation in the Amazon Basin.”

20) “The RF and IRF were normalized by their annual mean and standard deviation in order to compare both annual cycles.”

21) “The frequency of intense precipitation increases, mainly toward the end of the dry season, is related to the reduction in the inversion layer and an increase in CAPE and moisture due to the monsoon circulation (Machado et al., 2004).”

22) “This result indicates that in the dry period, when large scale precipitation decreases in the study area, most of the precipitation is linked to intense convection, which mainly occurs over elevated areas.”

23) “It is important to mention that the two last categories of elevations presented in Fig. 2 are more than 60 km from the radar. At this distance, the lower radar elevation band is around 1 km high,

which eliminates the ground clutter effect possibility.”

24) “As mentioned (Sect. 3), the terrain elevation plays an important role in triggering precipitation in the region, mainly during the dry season (Fig. 2b). In the statistics presented, no considerations were made in terms of the topography for the BC-precipitation relationship. However, to make sure that no considerations were necessary, a relevant test was performed in order to avoid misinterpretations of the conclusions regarding the comparisons between the rainfall characteristics and their association with BC concentrations. This test was made in order to verify whether the BC-precipitation relationship was different for each topography category presented in Fig. 2. So, for each category, we performed the statistical tests previously described, comparing RF values for different BC concentrations in stable and unstable atmospheres. The results for each terrain elevation category were statistically similar to Fig 4. Therefore, though important for triggering precipitation, the elevation did not influence the results related to BC-precipitation comparisons, which allowed us to use all grid points in our study independently of their elevation.”

25) No changes in the manuscript.

26) “The precipitation decrease could be related to a greater formation of cloud droplets with reduced size (Rosenfeld, 1999; Ramanathan et al., 2001), compromising the coalescence process (Kaufman et al., 2005), not allowing the droplets to grow to the required size and inhibiting precipitation and increasing evaporation.”

27) “Even apparently not being a dominant effect, an important test was applied in order to understand whether the scavenging process was significant in the study area. This test was performed because the main objective of this study was to identify the influence of BBA on precipitation. However, precipitation can also modify BBA concentrations in the atmosphere, due to the wet scavenging process. As mentioned previously, the BC measurements were made in situ, around 50 km from the city of Manaus, in the state of Amazonas. Thus, the concept of this test was based on eliminating from our statistics all samples whose precipitation was observed over the EUCAARI site. This elimination excluded the samples whose precipitation could have cleaned the atmosphere, throughout the scavenging process. After this, all the comparisons between the RF and BC concentrations were performed. Comparing the results when this criterion was utilized with those in which no aerosol wet scavenging consideration was performed, no significant differences were observed. This characteristic indicates that the local scavenging effect seems to be of a second order on the BC/rain interaction. However, this test does not take into account the reduction of BC sources outside the measurements site due to rainfall. Therefore, it is not possible to separate the scavenging effect from other physical effect associating reduction of rainfall to the increase in BC concentration, even if locally the scavenging effect seems to be of a second order.”

28) “The precipitation appears to spread over the region when the atmosphere is favorable to the development of convection associated with BBA.”

29) “Considering that high CAPE values are associated with stronger updrafts, the aerosol effect on the rainfall and in the severity of the convective processes could depend on the intensity of the vertical motions.”

30) “In order to understand whether the amount of cloud ice is influenced by the presence of high BBA concentrations, the IF index was calculated based on Eq. 3”.

31) “The RF-IF/BC analyses were useful in order to understand the increase/decrease in precipitation or ice fraction over the entire radar coverage area. However, they do not give information on the space and time scale organization of the rainfall. In order to evaluate whether

BBA change the lifetime duration of the rain cells, FORTRACC was employed. At first, rain cells which were the result of splitting or merging were eliminated in the statistics for the duration analysis. This was done due to the fact that precipitating cells which are the result of splitting or merging have their physical characteristics modified, influencing the duration and compromising the evaluation of the BBA effect on them. In addition, rain cells which do not have their entire lifecycle inside the radar domain were not considered, as it is not possible to know the duration of a rain cell which did not initiate and dissipate inside the radar domain. After this step, the number of rain cells whose lifecycle would be analyzed was drastically decreased. The result showed no significant change in the lifetime duration as a function of BBA. Unfortunately, the lifecycle rain cells population was not statistically significant after all these considerations. However, the study of the rain cell size distributions does not require any of these limitations, and all rain cells, regardless of whether they had their entire life cycle inside the domain region, can be taken into account.”

32) No changes in the manuscript.

33) No changes in the manuscript.

34) We preferred to add the word “filtering” before component, resulting in “filtering component”.

35) No changes in the manuscript.