The biomass aerosol influence on precipitation over the Central Amazon: An observational study

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1 Introduction

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; 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), Korenet 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).

2 Data analysis

All analyses performed in this study were made using a combination of four datasets:

1) 90×90 m^2 resolution of terrain elevation from the Shuttle Radar Topography Mission (SRTM);

2) Manaus S-Band Doppler Radar (1×1 km^2 horizontal resolution in a range of 100 km, every 11 min);

3) 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;

4) 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 then at 12 UTC.

It is important to clarify that BC is a byproduct of a partial combustion of fossil or wild fires (Ahmed et al., 2014), and it only represents around 5% of the total carbon concentration resulting from biomass burning (Formenti et al., 2001; Graham et al., 2003; Cozic et al., 2008). However, as BBA dominates the aerosol concentration in the Amazon Basin, BC was used in this research as an aerosol tracer. 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. (2008) 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.

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.

To determine the general behavior of precipitation in the study area, as well as its relationship with particulate material, three indices were used as follows:

$$RF = N_{20\ dBZ} / N_{TOTAL} \times 100 \quad (1)$$

$$IRF = N_{45\ dBZ} / N_{TOTAL} \times 100 \quad (2)$$

$$IF = N_{1\ mm} / N_{TOTAL} \times 100 \quad (3)$$

Where,

– RF is the Rain Fraction;

– IRF is the Intense Rain Fraction;

– IF is the Ice Fraction;

– $N_{20\,dBZ}$ is the amount of CAPPI-Ground pixels with a reflectivity equal or higher than 20 dBZ;

– $N_{45\,dBZ}$ is the amount of CAPPI-Ground pixels with a reflectivity equal or higher than 45 dBZ;

– $N_{1\,mm}$ is the amount of VIC pixels equal or higher than 1 mm;

– N_{TOTAL} is the sum of pixels in the area.

The Forecast and Tracking the Evolution of Cloud Clusters (FORTRACC), described in detail by Vila et al. (2008), is an algorithm capable of tracking the evolution of clouds systems. Originally, FORTRACC was used with infrared images from geostationary meteorological satellites. However, the FORTRACC version used in this study is an adaption for its application with meteorological radars. The FORTRACC was used to describe the size and duration of the rain cells. CAPPI-Ground images were used to track the rain cells around the city of Manaus. Rain cells were defined using the 20 dBZ threshold, which roughly corresponds to a rain rate of 1 mmh^{-1} according to Marshall and Palmer (1948).

As presented previously, the datasets did not have the same temporal sampling frequency. Thus a methodology in order to collocate them in time was applied. All variables derived from the radar samples (RF, IRF, IF and size and duration of the rain cells) selected to be used were collected within ± two hours difference from the atmospheric soundings. This consideration was made due to the fact that only two atmospheric soundings were available during each day. As a result, the atmospheric stability, inferred by CAPE, was considered constant with ± two hours of the sounding launching time. 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.

3 The seasonal evolution of black carbon concentration and convective processes

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. Generally, from previous research, the months of November and December present a high increase in the precipitation. However, only a slight increase in the normalized RF was observed (Fig. 1a). This behavior could be attributed to an observed El Niño configuration, which potentially decreases the precipitation in the Amazon. Another important aspect is that the normalized IRF is higher for the months within the dry period (Fig. 1a). 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). 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.

Even with small variations of terrain elevations, with the highest point around 160 m, a notable precipitation feature within the study domain is related to the topography (Fig. 2). For the rainy period (Fig. 2a) all elevations had a reflectivity peak greater than 20 dBZ (1 mm h^{-1}). In other words, even with a high peak of reflectivity being observed over elevated regions, during the rainy season precipitation occurs nearly homogeneously. During the dry season (Fig. 2b), reflectivity peaks greater than 20 dBZ are only observed over elevated areas. This suggests that in the absence of a large scale circulation, which could support the precipitation, the upslope triggering plays an important role in the formation of rain cells. 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. Thus, this area should receive special attention under forest protection policies. An important test was performed in order to ensure that the topography influence on the rainy systems would not lead to misinterpretations of the aerosol–precipitation relationship. Details of this test are presented in Section 4.

In addition to precipitation characteristics, the annual cycle of BC concentration (Fig. 1b) was another important consideration for the division of the analyses into rainy/dry periods. During the rainy season the BC concentration was below 700 ng m^{-3} for almost the entire period. This low concentration could be explained by wet deposition or the absence of large sources of biomass burning (Martin et al., 2010). On the other hand, for the six months that followed the BC concentration increased, mainly due to a high number of deforestation fires in the region (Artaxo et al., 2006) and less observed precipitation. This characteristic favors the outbreak of fires in the forest, allowing them to spread over the region. Thus, the combination of a period of the year (wet season) with more rain and less aerosol concentration, and the other season (dry season) with high BC concentrations and smaller amounts of rain but more intense precipitation events allowed us to reach interesting results.

4 The effect of instability on the rainfall–aerosol relationship

The first analysis performed was the overall relationship between BC concentrations and the rain characteristics (Fig. 3). At this stage, no consideration regarding the filtering of possible BBA effect on precipitation from another atmospheric feature was made. For the rainy period (Fig. 3b) a decrease in RF was observed as BC concentration increases. On the other hand, during the dry period (Fig. 3c), a decrease in RF was observed up to around 1000 ng m^{-3} of BC. After this value, the RF slightly increases. 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. At this stage, CAPE was chosen as the atmospheric component to be analyzed. Based on this, the precipitation/BC comparisons were performed for stable (CAPE < 1400 J kg^{-1}, less convective activity) and unstable (CAPE > 2600 J kg^{-1}, more convective activity) atmospheres. These values are similar to those presented by Wallace and Hobbs (2006), in order to divide the convective activity accordingly to the CAPE.

During the wet period, by the use of the atmospheric stability considerations, no differences were observed for the stable and unstable cases. The behavior was exactly the same as when no atmospheric considerations were performed (Fig. 3b). A similar pattern was observed for the stable case during the dry season (Fig. 4a). In support of this result, the RF distributions (Fig. 4c) present a more elongated tail for the small BC concentrations. This decrease could be associated with the suppression of warm or stratiform precipitation due to the fact that it is unlikely that a strong convection could form in stable cases. Although it was not possible to evaluate the cloud droplet size distribution by the dataset used in this study, a mechanism responsible for the observed behavior could be suggested. 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. The wet scavenging process, an important component responsible for the removal of aerosol in the atmosphere, could also contribute to the results presented, mainly for lower BC concentrations, where the RF reaches its higher value. Besides, it is not possible to define which effect dominates or what the feedback between them is. As the RF decreases for elevated BC concentrations, the wet deposition seems not to be the dominant effect on much polluted atmospheres, which gives support to the rain suppression theory. In addition, the radiative effect acts to increase the population of stable atmosphere cases and results in less rainfall for the situation of high aerosol loading.

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.

Similar comparisons between BC concentrations and RF which were performed for stable atmospheres were made for the unstable cases. The exact opposite behavior was found (Fig. 4b). The RF increased in cases where higher concentrations of BC were observed. The precipitation appears to spread over the region when the atmosphere is favorable to the development of convection associated with BBA. The distribution of RF for three categories of BC (Fig. 4d) shows that the greater the particulate material concentration, the more elongated the tail of the RF distributions. This result could be an indication that convection is invigorated by higher BBA concentrations (Lin et al., 2006; Graf, 2004; Rosenfeld et al., 2008; Altaratz et al., 2010; Koren et al., 2012). 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.

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.

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.

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. This stage was very important for the fact that ice formation could be influenced by BC (Demott et al., 1999; Cozic et al., 2008; Kireeva et al., 2009). Besides the convective case hypothesis, we could verify whether the precipitation suppression observed for the stable case is also linked to the presence of stratiform clouds. The mean IF values decreased substantially in proportion to the increase in BC concentration for stable atmospheres (Fig. 5a). This result could be an indication that stratiform clouds are negatively influenced by BBA. Another possibility could be associated to the fact that in the absence of strong buoyancy, the small droplets formed do not ascend to high atmospheric levels and evaporate easily or do not develop to a rainfall drop size, in a mechanism similar to warm precipitation suppression, which was described earlier. In addition, wet scavenging could also act to reduce BC concentration. In unstable cases, the result indicates that the convection invigoration hypothesis (Rosenfeld et al., 2008) through the presence of aerosols is likely to be true (Fig. 5b). An unstable atmosphere could carry the small droplets to higher levels, invigorating the convection and increasing the amount of ice (Rosenfeld et al., 2008). Besides, BC could be carried within the updrafts and act as ice nuclei. Which process is more important cannot be evaluated with the present dataset.

5 Rain cells size and duration

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 was 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. For the rainy season, no significant effect was observed on the rain cell size relationship with the BC concentration. The same pattern was observed for the dry season, except for rain cells, in unstable atmosphere, larger than 100 km^2. For systems smaller than 100 km^2, even in high instability cases, the increase in BC concentration does not show any significant relation with rain cell size. However, for larger rain cells (Fig. 6a), in unstable atmospheres during the dry season, the rain cell size increases as a function of the BC concentration. Even though a large variability can be noted in Fig. 6, the tail of the rain cells size distribution shows a larger size for higher BC concentration (Fig. 6b). Besides, the curves are significantly different at 95% of t test. The presence of particulate material appears to reinforce the convection that is well established by the elevated level of atmospheric instability. The mean systems area increases from 300 to over 900 km^2 as BC concentration varies from 300 to 1660 ng m^{-3}. The main reason of this size selection for high aerosol loading is a consequence of the increase in rain fraction and ice fraction that is associated to the rain cell size. However, this is probably also due to the entrainment effect, which depends inversely on cloud radii in the updrafts (Simpson and Wiggert, 1969). Larger rain cells have smaller entrainment favoring higher level of neutral buoyancy. Storelvmo (2012) also commented that the entrainment rate plays an important role on the aerosol effect on deep convective clouds. The main results presented in this study and the mechanisms proposed are summarized in Table 1.

6 Conclusions and discussions

In this study we have presented a methodology, using observational data, in order to contribute to the knowledge of the BBA effect on precipitating systems in the Amazon Basin. One of the greatest difficulties regarding this issue is filtering the aerosol effect from other important atmospheric features. Large-scale circulation or thermodynamic effects are a major component in the strengthening of convection. An analysis of the contribution of each effect could not be performed observationally, but throughout theoretical simulations which are not completely parameterized. In this study, CAPE values were used as the atmospheric filtering component, which allowed us to divide analyses according to the degree of atmospheric stability. Important features, such as wet scavenging, synoptic scale influence and droplet size distribution characteristics, need further study and improvement to extend this result. As BBA is predominant in the Amazon Basin, BC was used as an aerosol tracer. Nevertheless, other kinds of aerosol are also present in the region and should receive more attention in new field campaigns. 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.

Despite the limitations due to the database and the large set of independent variables, the results presented in this study were statistically significant and physically relevant. BBA releases into the atmosphere generally appear to contribute to a decrease in precipitation. However, it is difficult to prove this behavior because there are several effects, such as wet scavenging or atmosphere inhibitions where the effect cannot be excluded from the results and could also contribute to precipitation reduction. 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. However, the vertical velocity can be directly linked to CAPE values, as the greater the atmospheric instability the stronger the updrafts. The study does not define any specific BC concentration which could activate the cloud process, thereby increasing convective strengthening. Nevertheless, it is shown that this process only occurs significantly when the BC concentration is higher than 1200 ng m^{-3}, which can contribute to generating a large number of droplets due to the microphysical effect. Wet scavenging appears to be of a second order in the precipitation/aerosol relationship for elevated concentrations of BC. However, it is only possible to have a qualitative result because it was not possible to isolate this process for the precipitation inhibition cases and quantify the exact effect on the rain and ice fractions.

The indication of the influence of BBA on the size of the rain cells followed the same behavior observed for RF and IF. We also suggest that the effect is modulated by the atmospheric degree of instability. An important size threshold was found, and the relationship between BC concentration and rain cells area depended on it. The influence of BBA on the convective strengthening was observed for large rain cells. It is probably related to the smaller entrainment of dry air parcel into the convection, favoring a higher level of neutral buoyancy. The area increase was just observed, for the unstable case in the dry period, for systems larger than 100 km^2. Although the results of the BBA influence on the duration of the rain cells have been inconclusive, some evidence of this relationship should be mentioned. It is well-known that the size of rain cells is positively correlated to their duration. So, the results presented in this study could be an indication that high concentrations of BC could lead to longer lifetime rain cells, depending on the atmospheric degree of instability.

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Figures and Tables

Table 1. Observed features and proposed mechanisms for stable and unstable atmospheres during dry and wet season

Atmosphere State Wet season	Observed Features	Possible Mechanisms Explaining this behaviour:
Stable (CAPE<1400 J/kg)	- Rain and Ice Fraction decreases as BC increases ; - Low BC concentration; - No influence on rain cell size;	- The wet scavenging process, greater formation of cloud droplets with reduced size suppressing precipitation; - Atmosphere stabilization;
Unstable (CAPE>2600 J/kg)	- Rain and Ice Fraction decreases as BC increases; - Low BC concentration; - No influence on rain cell size;	- The wet scavenging process, greater formation of cloud droplets with reduced size suppressing precipitation;
Atmosphere State Dry season	**Observed Features**	**Possible Mechanisms Explaining this behaviour:**
Stable (CAPE<1400 J/kg)	- Rain and Ice Fraction decreases as BC increases; - High polluted atmosphere (>1000 ng/m^3); - No influence on rain cell size;	- The wet scavenging process, greater formation of cloud droplets with reduced size suppressing precipitation; - Atmosphere stabilization; - Less buoyancy; - Weaker updrafts; – Weaker homogenous ice formation;
Unstable (CAPE>2600 J/kg)	- Rain and Ice Fraction increases as BC increases; - High polluted atmosphere (>1000 ng/m^3); – Increase of rain cell size as BC increases, only for large rain cell areas (>100 km^2)	- High buoyancy; - Stronger updrafts; - High homogenous ice formation; - More latent heating; - Convection invigorated; - Smaller entrainment for large rain cells

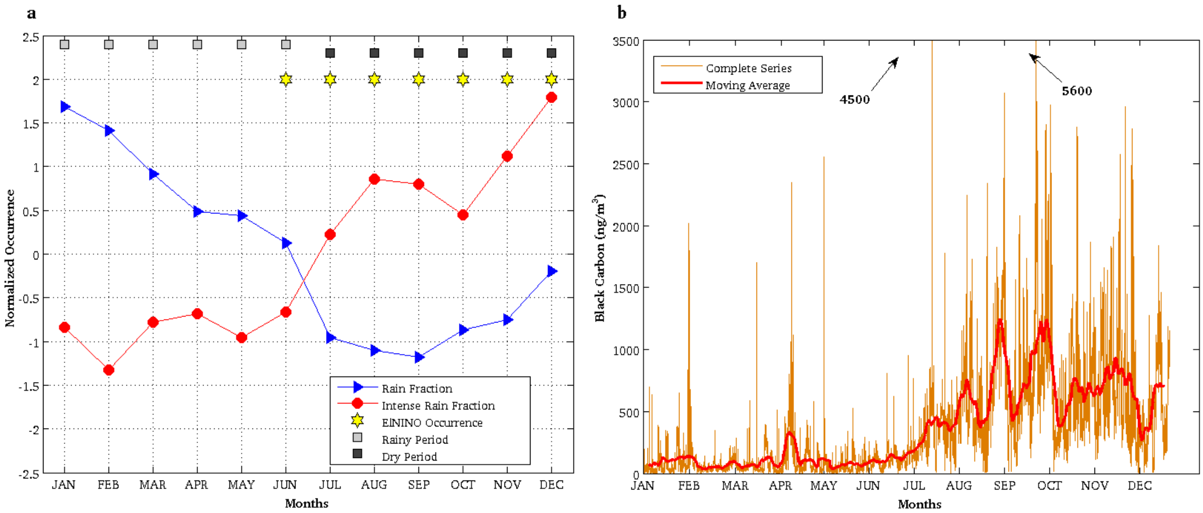

Figure 1. (a) Annual Cycle of rain fraction (RF) and intense rain fraction (IRF) normalized by its annual mean and standard deviation for the S-band radar located in Manaus in 2009. The symbols on the top of the panel represent: The rainy period (light gray squares); the dry period (dark gray squares); El Niño occurrence (yellow stars). (b) Annual Cycle of BC for Manaus-AM in 2009. The orange line represents the complete series, in 30-minute intervals for each measurement and the thick red line represents a weekly moving average.

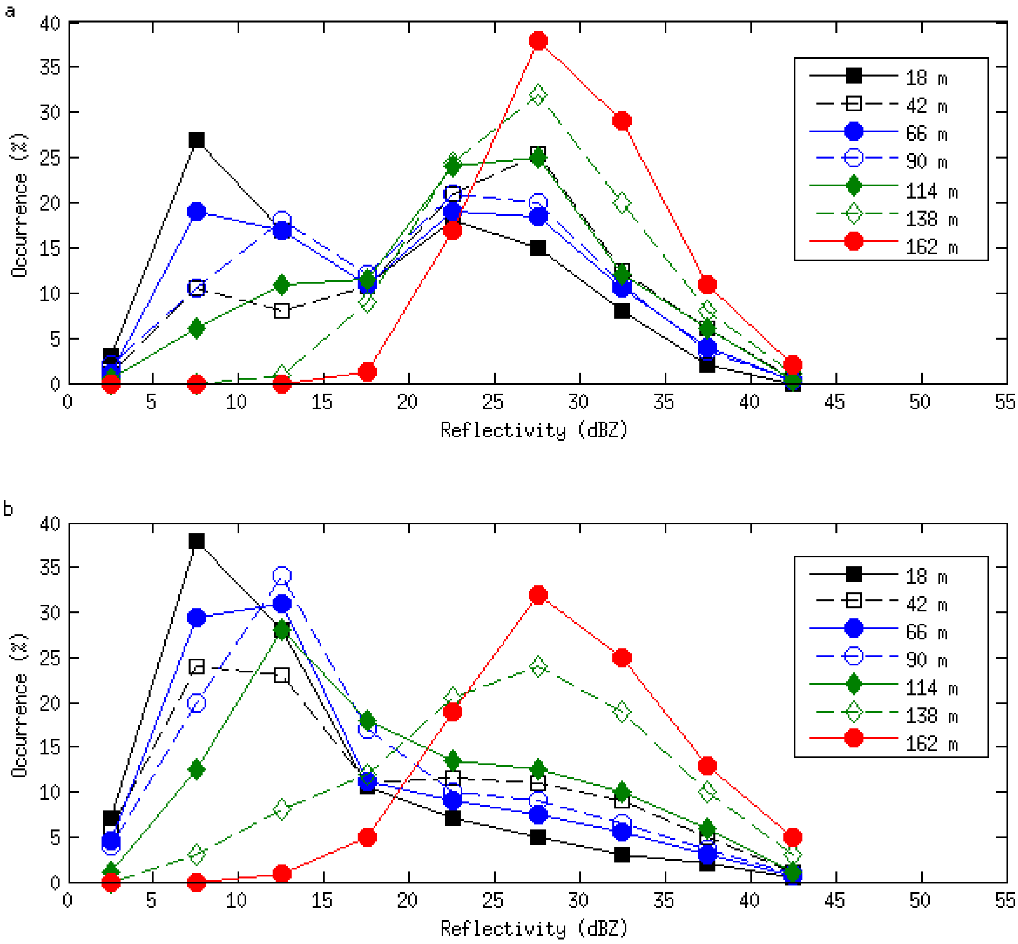

Figure 2. Frequency histograms of radar reflectivity for different topography elevations (intervals of 24 m) for the S-band radar located in Manaus in 2009. (a) rainy season and (b) dry season.

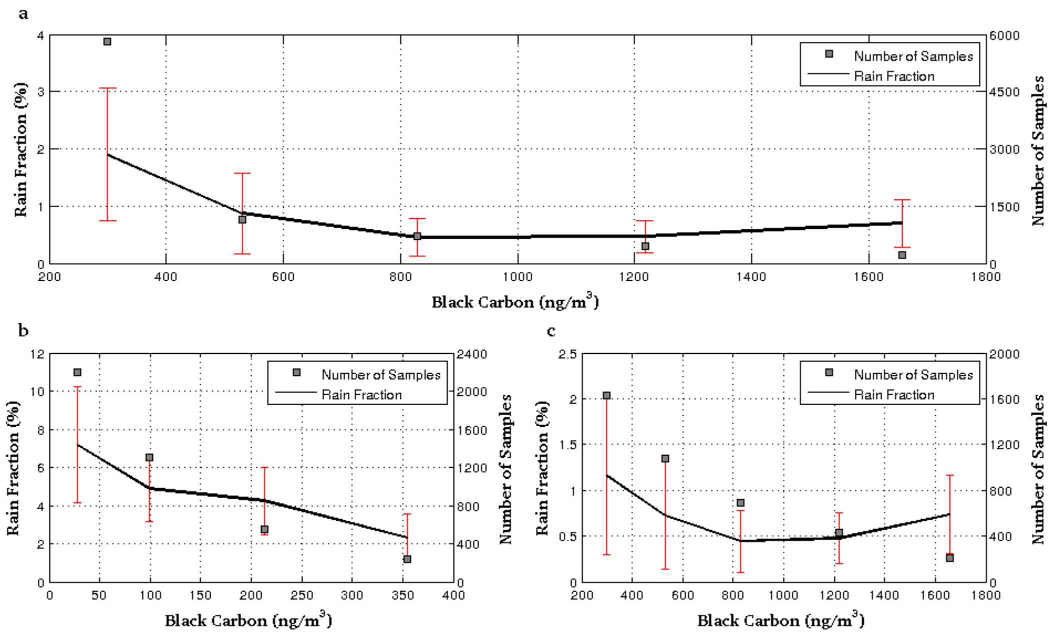

Figure 3. Mean, standard deviation and number of samples of rain fraction (RF) for different Black Carbon (BC) concentrations. (a) The entire year; (b) Rainy Season; (c) Dry season. For these curves, no atmospheric stability consideration was performed.

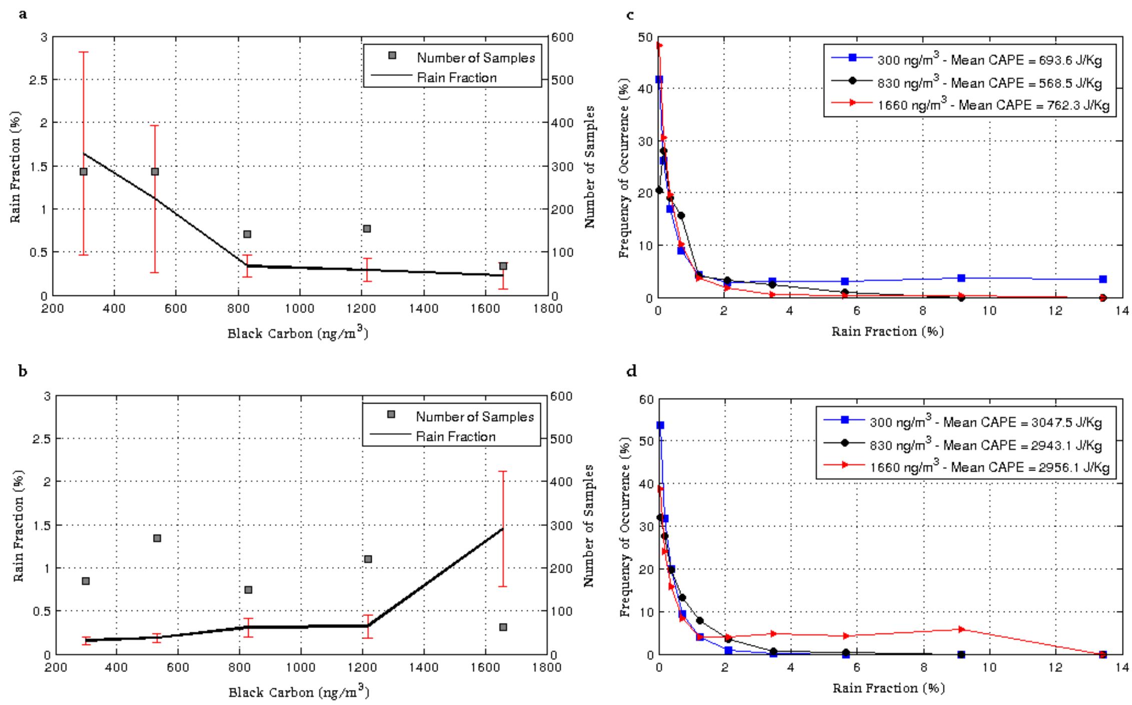

Figure 4. Mean, standard deviation and number of samples of rain fraction (RF) for different Black carbon (BC) concentrations for stable (a) and unstable (b) atmospheres in the dry period. Rain fraction (RF) frequency histograms for the first, third and fifth Black Carbon (BC) concentrations in (a) and (b), for stable (c) and unstable (d) atmospheres. The first and third curves in (c) and (d) are significantly different at 95% for the t-test.

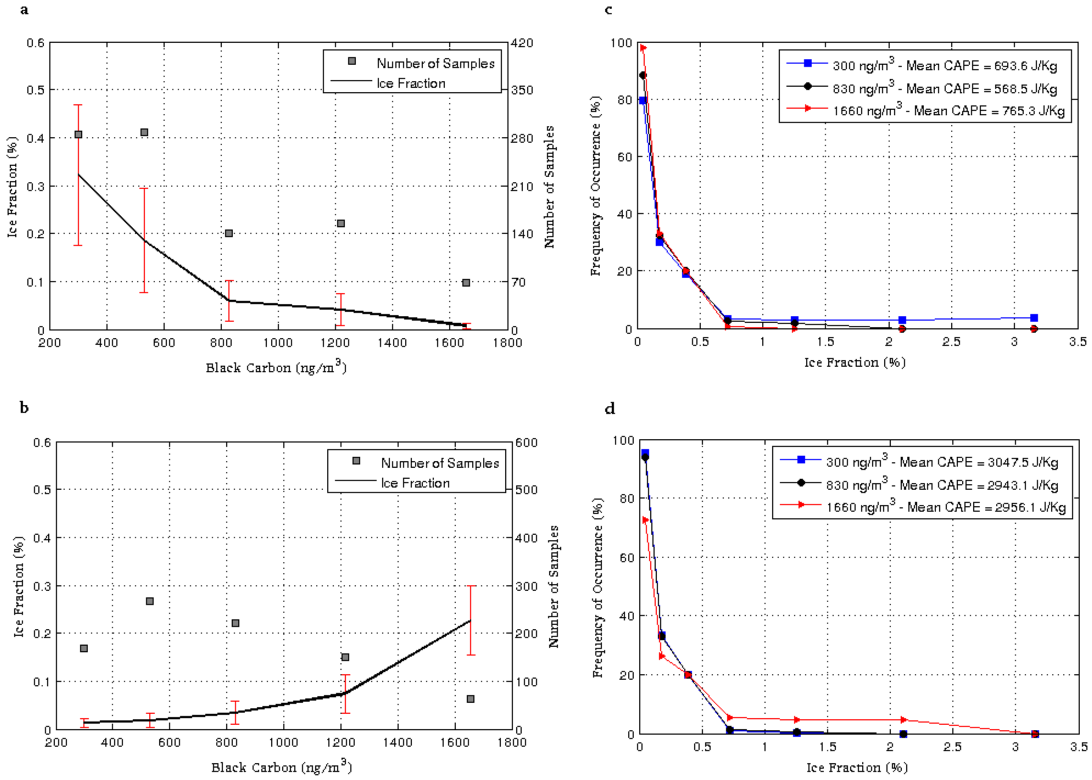

Figure 5. Mean, standard deviation and number of samples of ice fraction (IF) for different Black Carbon (BC) concentrations for stable (a) and unstable (b) atmospheres in the dry period. Rain fraction (RF) frequency histograms for the first, third and fifth Black Carbon (BC) concentrations in (a) and (b), for stable (c) and unstable (d) atmospheres. The first and third curves in (c) and (d) are significantly different at 95% for the t-test.

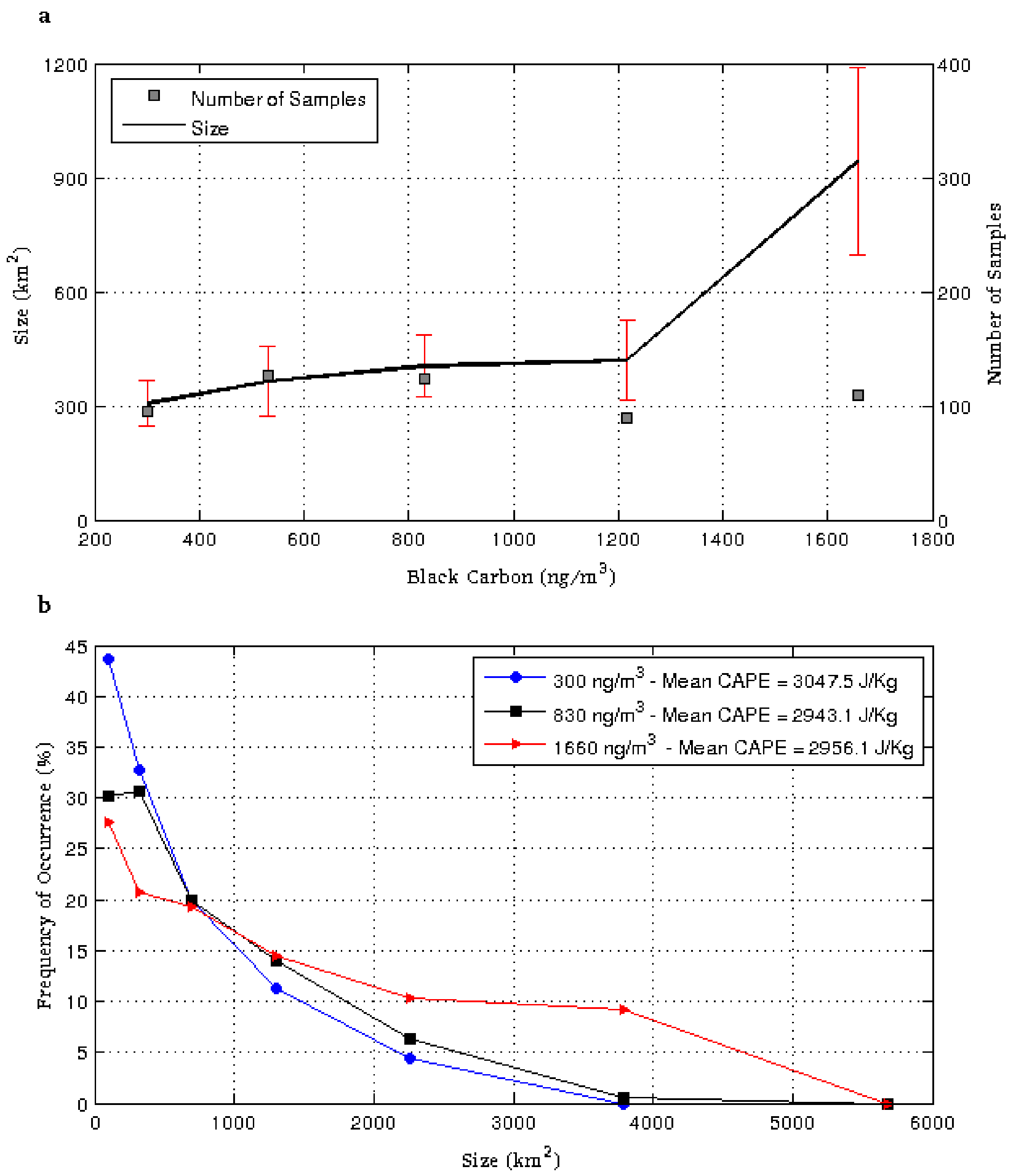

Figure 6. (a) Mean, standard deviation and number of samples of rain cells size (>100km^2) for different Black carbon (BC) concentrations in an unstable atmosphere during the dry period; (b) Size frequency histograms for the first, third and fifth Black Carbon (BC) concentrations in (a). The first and third curves in (b) are significantly different at 95% for the t-test.