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

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Abstract

Understanding the aerosol influence on clouds and precipitation is an important key to reduce uncertainties in simulations of climate change scenarios with regards to deforestation fires. Here, we associate rainfall characteristics obtained by an S-Band radar in the Amazon with in situ measurements of biomass burning aerosols for the entire year of 2009. The most important results were obtained during the dry semester (July–December). The results indicate that the aerosol influence on precipitating systems is modulated by the atmospheric instability degree. For stable atmospheres, the higher the aerosol concentration, the lower the precipitation over the region. On the other hand, for unstable cases, higher concentrations of particulate material are associated with more precipitation, elevated presence of ice and larger rain cells, which suggests an association with long lived systems. The results presented were statistically significant. However, due to the limitation imposed by the dataset used, some important features such as wet scavenging and droplet size distribution need further clarification. Regional climate model simulations in addition with new field campaigns could aggregate information to the aerosol/precipitation relationship.

1 Introduction

The Amazon Forest faces every year a large amount of aerosol from pasture and forest fires (Artaxo et al., 2002, 2006; Martin et al., 2010), and the pollution plumes generated could spread over large areas (Martin et al., 2010). The Amazon Biomass Burning Aerosol (BBA) affects the atmospheric composition (Ryu et al., 2007) and could potentially influence the 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 in the second semester of the year, is the period that faces the greater biomass burning emissions (Artaxo et al., 2002; Altaratz et al., 2010; Martin et al., 2010; Camponogara et al., 2014). However, during the first semester (wet period), BBA is also observed in the Amazon Basin (Martin et al., 2010).

In the past years, the scientific community has gathered efforts on understanding the effect of aerosols on cloud and precipitation in order to reduce uncertainties in climate prediction (Tao et al., 2012). The first warm rain suppression evidence was documented by Rosenfeld (1999). In the following years, similar results were also obtained and presented in the literature (Nober et al., 2003; Koren et al., 2004; Diehl et al., 2007; Qian et al., 2009). The suggested mechanism for warm rain suppression is related to the fact that aerosols could act as cloud condensation nuclei. A great formation of small cloud droplets occur in polluted environments (Rosenfeld, 1999; Ramanathan et al., 2001; Nober et al., 2003; Qian et al., 2009), which compromises the coalescence process (Kaufman et al., 2005). These droplets do not reach the required size for precipitating and can evaporate rapidly (Artaxo et al., 2006).

Based on the evidences of warm rain suppression over regions with forest fires, Diehl et al. (2007) suggested that the ice phase could be an essential factor in the rain process. In fact, laboratories measurements indicate the high capacity of ice nucleation by BBA (Petters et al., 2009). In the past years, some studies suggested that deep convective clouds are invigorated by the presence of aerosols from vegetation fires (Andreae et al., 2004; Lin et al., 2006; Myhre et al., 2007; Rosenfeld et al., 2008; Altaratz et al., 2010; Koren et al., 2012; Storer and Heever, 2013). Rosenfeld et al. (2008) proposes a conceptual model based on the effect of aerosols on deep convective cells. Accordingly to the authors, due to the high concentration of aerosols in polluted environments, the raindrops nucleation process would be slower than in unpolluted areas. Besides, in atmospheres favourable to a deep convective activity, these droplets and the aerosols could ascend in the atmosphere, reaching the freezing level. Over a certain time, the cloud accumulates higher liquid water and ice contend, favouring more intense rainfall rates and increasing electrical activity (Graf, 2004). Even with the evidences, the cloud invigoration process by aerosols still needs more clarifications (Altaratz et al., 2014).

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Although well documented, especially in recent years, the BBA effect on clouds and precipitation is still a source of debate in scientific community. Important aspects such as the size and duration of precipitating cells require further clarification. Thus, the main objective of this research was to contribute to the actual scientific knowledge of the BBA influence on precipitation using ground base measurements. Size, duration, precipitation and ice content were the characteristics studied for the analyzed systems over the largest Amazon City (Manaus-AM in Brazil).

2 Data analysis

All analyses performed in this research were made using a combination of four datasets: 90 m × 90 m resolution of terrain elevation from the Shuttle Radar Topography Mission (SRTM); S-Band Doppler Radar (1 km × 1 km horizontal resolution in a range of 100 km, every 11 min); 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; and atmospheric soundings, which were collected twice a day, at 00:00 and 12:00 UTC. These 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). Almost all data sets were collected from the city of Manaus-Brazil, except the BC concentrations, which were measured about 50 km from the city. The EUCAARI experiment used the instrument Multi-Angle Absorption Photometer (MAAP) (Slowik et al., 2007).

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 by its potential for ice nucleation, what 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 lower tropospheric mixed phase clouds also present BC as cloud droplet nuclei. Another important aspect related to BC particles is its capacity of absorbing 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. Based on BC physical characteristics, it is being considered one important component of international negotiations (Shindell et al., 2012).

The S-band radar data was processed following the TRADHy strategy (Delrieu et al., 2009), briefly recalled hereafter. A preliminary quality control of the radar data was performed and the radar calibration was checked throughout the 2009 year. The detection domain was determined for each elevation angle with characterizing screening effects and clutters. Identifications were carried out to dynamically determine rain types and the corresponding vertical profiles of reflectivity (VPR). For the VPR identification, the initial method described in Delrieu et al. (2009) and Kirstetter et al. (2010) was replaced by a physically-based method (Kirstetter et al., 2013) for more robustness. The VPR method compares radar data at different distances and altitudes to account for sampling effects and identify a representative VPR over the radar domain for a given precipitation type. Corrections for both clutter and screening effects were performed along with a projection of measured reflectivities onto the ground level using rain-type VPRs. At a given pixel, reflectivities from all available elevation angles were used for the projection. As a final step, reflectivity–rain-rate conversion (Z–R relationships) that depends on rain type was applied on the reflectivity field to estimate rain rates at ground level. Through the use of this technique, it was possible to extrapolate the radar reflectivity to a constant altitude plan at the same elevation of the radar, which was named as Constant Altitude Plan Position Indicator-Ground (CAPPI-Ground). The Vertical Ice Content (VIC) for each pixel of the radar images was also calculated. To

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

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

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

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

Where,

- RF is the Rain Fraction;
- IRF is the Intense Rain Fraction;
- IF is the Ice Fraction;
- $N_{20\,\mathrm{dBZ}}$ is the amount of CAPPI-Ground pixels with a reflectivity equal or higher than 20 dBZ;
- $N_{45\,\mathrm{dBZ}}$ is the amount of CAPPI-Ground pixels with a reflectivity equal or higher than 45 dBZ;
- $N_{1\,\mathrm{mm}}$ 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 details by Vila et al. (2008), is an algorithm capable of tracking the evolution of clouds systems. Originally, the FORTRACC was used with infrared images from geostationary meteorological satellites. However, the FORTRACC version used in this research 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-AM. Rain cells were defined using the

20 dBZ threshold, which roughly corresponds to a rain rate of 1 mm h^{-1} accordingly to Marshall and Palmer (1948).

As presented previously, the datasets did not have the same sampling time. Then, 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. Then the atmospheric stability, inferred by CAPE, was considered constant with ± two hours of the sounding laughing time. As this issue was not observed for the sampling time of EUCAARI measurements, the BC concentrations 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 the 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 which the normalized RF was greater/smaller than zero were considered rainy/dry periods. Generally, from previous research, the months of November and December presents a high increase in the precipitation. However, only a slight augment of the normalized RF was observed (Fig. 1a). This behaviour 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 has greater values for the months within the dry period (Fig. 1a). The intense precipitation increases, mainly toward the end of the dry season, is related to the reduction of the inversion layer and an increase of CAPE and moisture due to the

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monsoon circulation (Machado et al., 2004). This result indicates that as total rainfall area decreases, more intense convection is developed.

Even with small variations of terrain elevations, with maximum 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 high peak of reflectivity being observed over elevated regions, during the rainy semester the 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 on the formation of rain cells. 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 on the aerosol–precipitation relationship. Details of this test are presented in Sect. 4.

In addition to precipitation characteristics, the annual cycle of BC concentration (Fig. 1b) was another important consideration for dividing the analyses in 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 by 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 great number of deforestation fires in the region (Artaxo et al., 2002, 2006) and less observed precipitation. This characteristic favors the fires maintenance in the forest, allowing it to spread out over the region. Then, the combination of a period of the year (wet season) with more rain and less aerosol concentration and another season (dry season) with high BC concentrations and smaller amounts of rain but more intense precipitation events allowed us to reach interesting results.

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4 The effect of instability in the rainfall–aerosol relationship

To avoid misinterpretations on the conclusions regarding to the comparisons between the rain cells characteristics and their association with BC concentrations a relevant test was applied. As commented previously (Sect. 3), the terrain elevation plays an important role on triggering the precipitation, mainly during the dry season (Fig. 2b). Based on this, the statistics presented in this research, starting in this section, were first performed accordingly to the topography categories presented in Fig. 2. This test was made in order to verify if the BC-precipitation relationship was different for terrains with different elevations. However, no differences were observed between the analysis without any consideration and the topography test. In addition, the BC-precipitation relationship was the same for all elevations. Then, this result made us not to do any topography consideration regarding to the BC-precipitation relationship, allowing us to use all grid points in our study domain independently of their elevation.

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

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During the wet period, by the use of the atmospheric stability considerations, no differences were observed for the stable and unstable cases. The behaviour 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 research, a mechanism responsible for the observed behaviour 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 up to the required size for precipitating. The wet scavenging process, an important component responsible for the aerosol removal in the atmosphere, could also contributes to the results presented, mainly for lower BC concentrations, where the RF reaches its bigger value. Besides, it is not possible to define which effect dominates or how is the feedback between them. 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.

An important test, in order to give indications of wet scavenging process occurrence, was applied. The test was extremely important by the fact that the main objective of this research was identifying the influence of BBA on the precipitation. The opposite affect also exists, and even being hard to be separated, an important criterion was used. As the BC concentration measurement used in this research was punctual, 50 km distant from the city of Manaus-AM, all samples in which rainfall was observed exactly over the EUCAARI measurement site were not considered while performing the same statistics which started to be presented in this section. Comparing the results when this criterion was utilized with the ones in which no aerosol wet scavenging consideration was performed, no 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 second order.

The exact opposite behaviour was found for unstable atmospheres (Fig. 4b). The RF increased in cases where higher concentrations of BC were observed. The precipitation appears to spread out when the atmosphere is favourable 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). Although not being possible to be quantified, the wet scavenging seems to be of second order, and would act in the opposite direction by the fact that precipitation did not decrease BC concentration at any point of the curve (Fig. 4b). Considering that large CAPE is associated to stronger updrafts, the aerosols effect in the rainfall and in the stretching of the convective processes could depends on the intensity of the vertical motions. During the dry season only the upslope regions trigger convection and in the highly unstable cases it appears that BBA contributes to increase ice nucleus, increasing precipitation.

In order to understand whether the amount of cloud ice is influenced by the presence of high BBA concentrations the IF index was calculated. This stage was very important by 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 of 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 the warm precipitation suppression, which was previously described. In addition, the wet scavenging could also act to reduce ice fraction as BC increases. In unstable cases, the result indicates that the convection invigoration hypothesis (Rosenfeld et al., 2008) by the presence of aerosols is likely true (Fig. 5b). An unstable atmosphere could carry the small droplets to higher levels and invigorating the convection (Rosenfeld et al., 2008). Besides, BC could be carried within the updrafts and acting as ice nuclei.

5 Rain cells size and duration

The RF-IF/BC analyses were useful in understanding the increase/decrease of the precipitation or ice fraction over the entire radar area. However, it does not give information about the space and time scale organization of the rainfall. In order to study this important aspect, the FORTRACC was applied to the entire year to compute the life cycle of the rain cells and compare it with BC concentrations. The analyses of the duration of the rain cells were inconclusive due to substantial sampling decrease when just rain cells which had their entire life cycle inside the study domain, without merge and split, were considered and will not be presented. However, considering all rain cells, independently if they had their entire life cycle inside the domain region, interesting results related to cells size were obtained.

For the rainy season, no significant effect was observed in the rain cell size relationship with BC concentration. The same pattern was observed for the dry season, except for rain cells, in unstable atmosphere, larger than 100 km^2. For system smaller than 100 km^2, even in high instability cases, the increase in BC concentration does not show any significant relation with rain cells size. However, for larger rain cells (Fig. 6a), in unstable atmospheres during the dry season, the rain cells size increases as function of the BC concentration. Even if a large variability can be noted in Fig. 6, the tail of the rain cells size distribution shows larger size for larger 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 $ng\,m^{-3}$. This is probably due to the entrainment effect, which depends inversely on cloud radii in the updrafts (Simpson and Wiggert, 1969). Larger rain cells have smaller entrainment favouring higher level of neutral buoyancy. Storelvmo et al. (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 research and the mechanisms proposed are sumarized a Table 1.

6 Conclusions and discussions

In this research we have presented a methodology, using observational data, in order to contribute on the knowledge of the BBA effect on precipitating systems in the Amazon Basin. One of the greatest difficulties regarding to this issue is filtering the aerosol effect from other important atmospheric features. Large-scale circulation or thermodynamic effects are also important parameters to be analyzed. An analysis of the contribution of each effect could not be performed observationally, but throughout theoretical simulations which are not completely parameterized. However, effects such as lower level convergence could not influence the results, due to the regional characterization of the dataset used. In this research, CAPE values were used as the atmospheric component, which allowed us to divide the analyzes accordingly 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.

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Despite of the limitations due to the database and the large set of independent variables, the results presented in this research were statistically significant and physically relevant. BBA releases in the atmosphere appear to contribute to a decrease in precipitation. However, it is difficult to prove this behaviour because there are several effects, such as wet scavenging or atmosphere inhibitions which the sign cannot be excluded from the results and could also contribute to the precipitation reduction. Nevertheless, 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 others features act to reduce precipitation in polluted atmospheres, as wet scavenging for example. 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, the greater is the atmospheric instability, the stronger are 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 BC concentration is higher than $1200\,\mathrm{ng\,m^{-3}}$. The wet scavenging appears to be of 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 exactly effect in the rain and ice fractions.

The indication of the influence of BBA on the size of the rain cells followed the same behaviour observed for RF and IF. We also suggest that the effect is modulated by the atmospheric instability degree. 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 just for large rain cells. It is probably related to the smaller entrainment of dry air parcel into the convection, favouring higher level of neutral buoyancy. The area increase was just observed, for the unstable case in the dry period, for systems bigger than $100\,\mathrm{km^2}$. Although the results of the

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BBA influence on the duration of the rain cells have been inconclusive, some evidences of this relationship should be commented. It is well known that the size of rain cells is well correlated with its duration. So, the results presented in this research could be an indication that high concentrations of BC could lead to long life rain cells, depending on the atmospheric instability degree.

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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 $J\,kg^{-1}$)	– 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 $J\,kg^{-1}$)	– 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;
Atmosphere State Dry season	**Observed Features**	**Possible Mechanisms Explaining this behaviour:**
Stable (CAPE < 1400 $J\,kg^{-1}$)	– 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 $J\,kg^{-1}$)	– 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;

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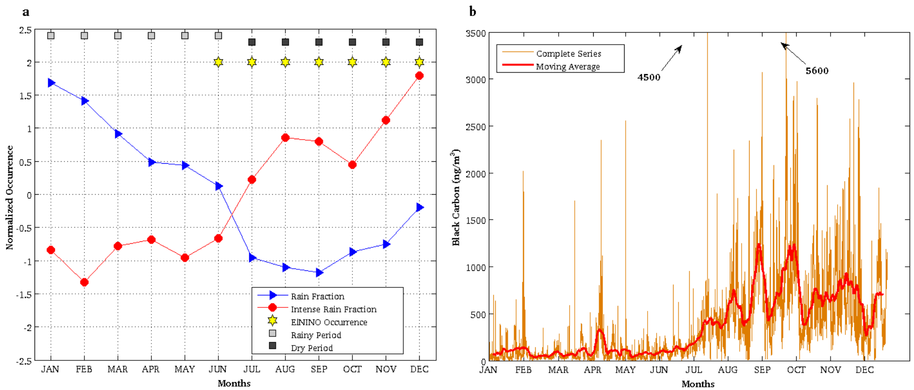

Figure 1. (a) Annual cycle of RF and IRF normalized by its annual mean and standard deviation for the S-band radar located in Manaus in 2009. The symbols on the top of the panel represent: the rainy period (light gray squares); the dry period (dark gray squares); El Niño occurrence (yellow stars). **(b)**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

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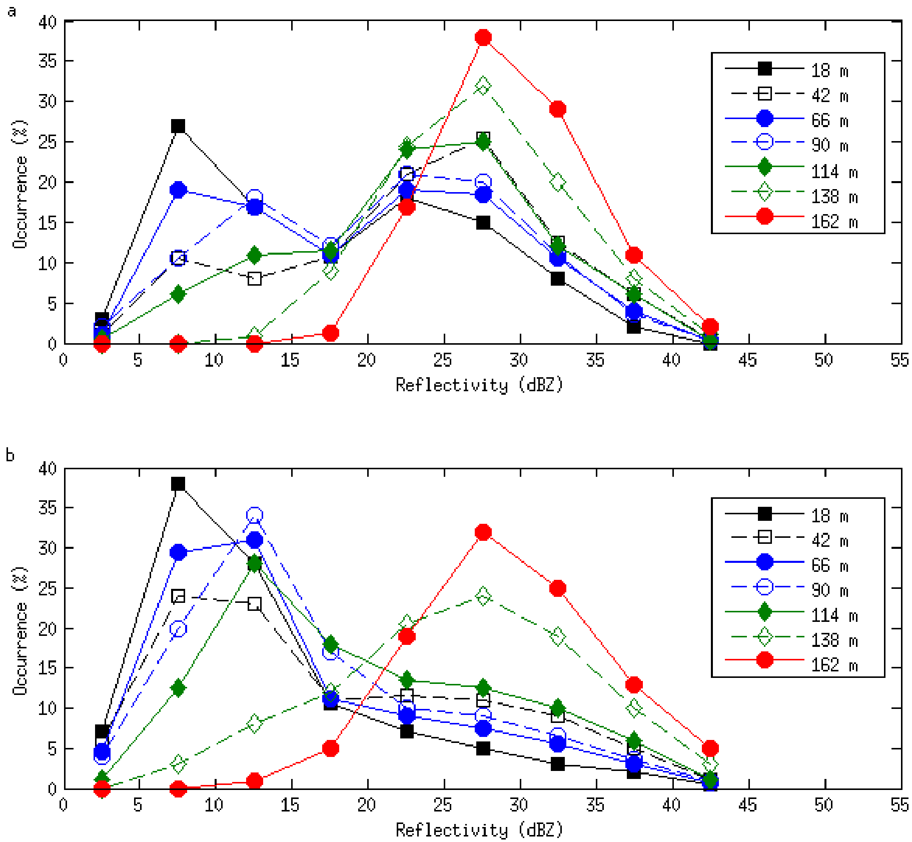

Figure 2. Frequency histograms of radar reflectivity for different topography elevations (intervals of 24 m) for the S-band radar located in Manaus in 2009. **(a)** Rainy season and **(b)** dry season.

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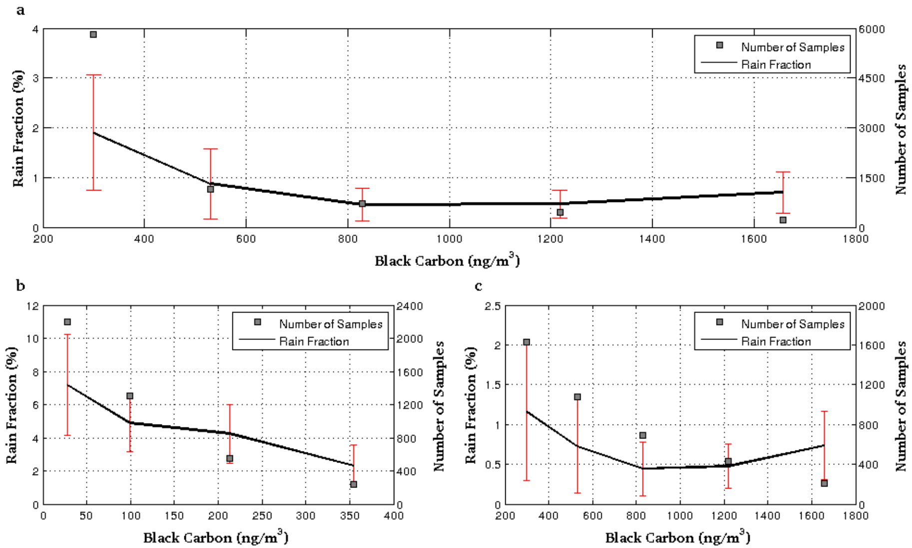

Figure 3. Mean, standard deviation and number of samples of RF for different BC concentrations. **(a)** The entire year; **(b)** rainy season; **(c)** dry season. For these curves, no atmospheric stability consideration was performed.

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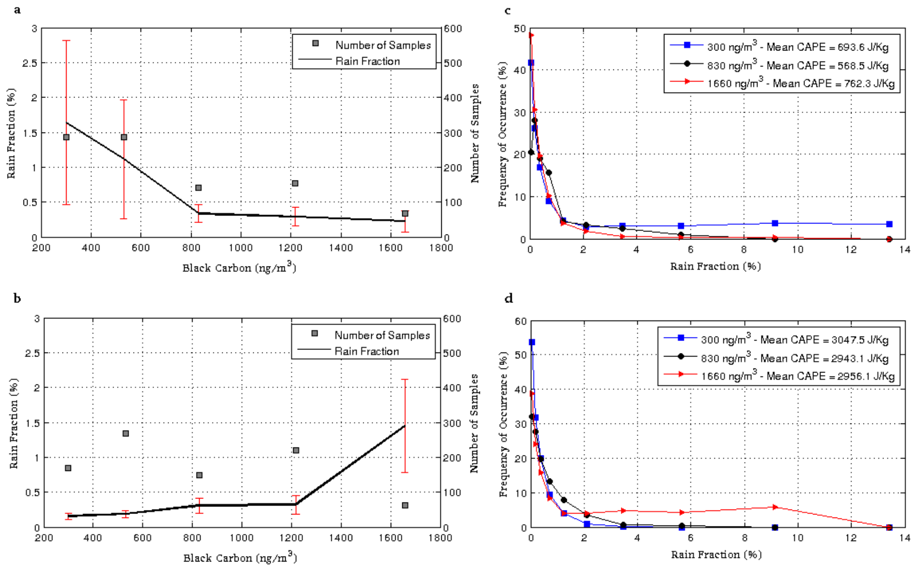

Figure 4. Mean, standard deviation and number of samples of RF for different BC concentrations for stable **(a)** and unstable **(b)** atmospheres in the dry period. RF frequency histograms for the first, third and fifth BC concentrations in **(a)** and **(b)**, for stable **(c)** and unstable **(d)**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

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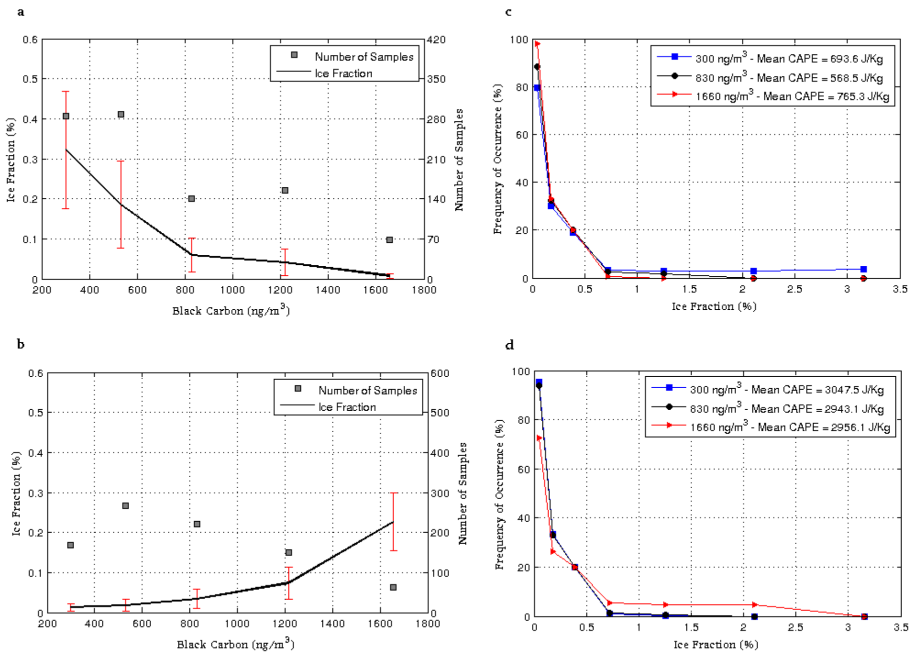

Figure 5. Mean, standard deviation and number of samples of IF for different BC concentrations for stable **(a)** and unstable **(b)** atmospheres in the dry period. RF frequency histograms for the first, third and fifth BC concentrations in **(a)** and **(b)**, for stable **(c)** and unstable **(d)**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

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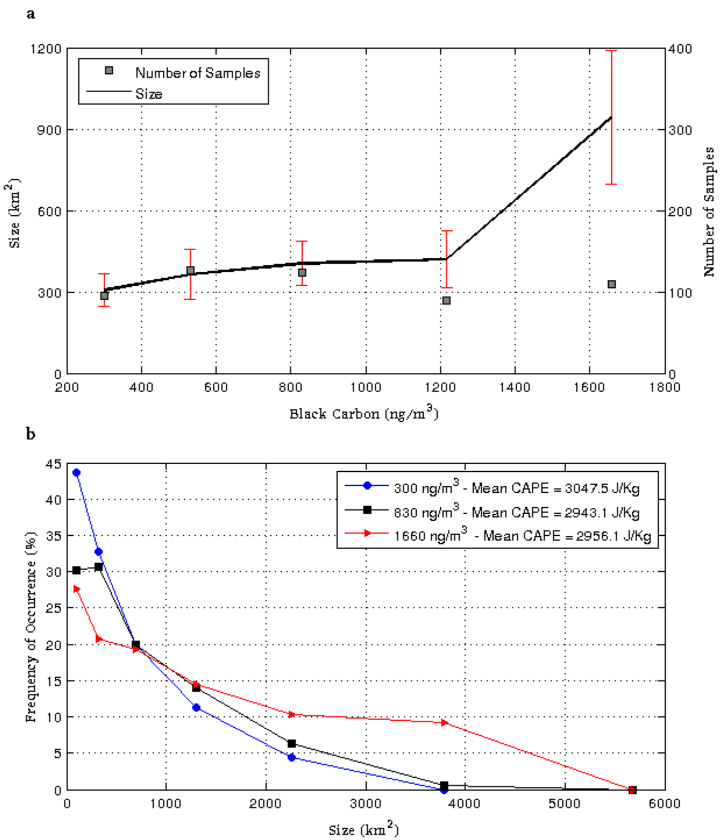

Figure 6. (a) Mean, standard deviation and number of samples of rain cells size (> 100 km^2) for different BC concentrations in an unstable atmosphere in the dry period; **(b)** size frequency histograms for the first, third and fifth BC concentrations in **(a)**. The first and third curves in **(b)**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

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