

# Optical and Geometrical Properties of Cirrus Clouds in Amazonia Derived From 1-year of Ground-based Lidar Measurements

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**Abstract.** Cirrus clouds cover a large fraction of tropical latitudes and play an important role in Earth's radiation budget. Their optical properties, altitude, vertical and horizontal coverage control their radiative forcing, and hence detailed cirrus measurements at different geographical locations are of utmost importance. Studies reporting cirrus properties over tropical rain forests like the Amazon, however, are scarce. Studies with satellite profilers do not give information on the diurnal cycle, and the satellite imagers do not report on the cloud vertical structure. At the same time, ground-based lidar studies are restricted to a few case studies. In this paper, we derive the first comprehensive statistics of optical and geometrical properties of upper-tropospheric cirrus clouds in Amazonia. We used one year (July 2011 to June 2012) of ground-based lidar atmospheric observations north of Manaus, Brazil. This dataset was processed by an automatic cloud detection and optical properties retrieval algorithm. Upper-tropospheric cirrus clouds were observed more frequently than reported previously for tropical regions. The frequency of occurrence was found to be as high as 88 % during the wet season and not lower than 50 % during the dry season. The diurnal cycle shows a minimum around local noon and maximum during late afternoon, associated with the diurnal cycle of precipitation. The mean values of cirrus cloud top and base heights, cloud thickness and cloud optical depth were  $14.3 \pm 1.9$  (std) km,  $12.9 \pm 2.2$  km,  $1.4 \pm 1.1$  km, and  $0.25 \pm 0.46$ , respectively. Cirrus clouds were found at temperatures down to  $-90$  °C. 6 % of the Cirrus clouds were above the base of the tropical tropopause layer. The vertical distribution was not uniform, and thin and subvisible cirrus occurred more frequently closer to the tropopause. The mean lidar ratio was  $23.3 \pm 8.0$  sr. However, for subvisible cirrus clouds a bimodal distribution with a secondary peak at about 44 sr was found suggesting a mixed composition. A dependence of the lidar ratio with cloud temperature (altitude) was not found, indicating that the clouds are vertically well mixed. The frequency of occurrence of cirrus clouds classified as subvisible ( $\tau < 0.03$ ) were 41.6 %, whilst 37.8 % were thin cirrus ( $0.03 < \tau <$

0.3) and 20.5 % opaque cirrus ( $\tau > 0.3$ ). Hence, in central Amazonia not only a high frequency of cirrus clouds occurs, but also a large fraction of subvisible cirrus clouds. This high frequency of subvisible cirrus clouds may contaminate aerosol optical depth measured by sun-photometers and satellite sensors to an unknown extent.

## 1. Introduction

Clouds cover on average about 50 % of the Earth's surface (Mace et al., 2007) and cirrus alone cover 16.7 % (Sassen et al., 2008), with higher fractions occurring in the Tropics (Sassen et al., 2009). Hence cirrus are important to understand current climate and to predict future climate (Wylie et al. 2005, Stubenrauch et al. 2006; Nazaryan et al., 2008). Several studies emphasize the important role that cirrus clouds play in the Earth's radiation budget (i.e. Liou 1986; Lynch et al. 2002; Yang et al. 2010a). Their role is twofold. First, cirrus clouds increase warming by trapping a portion of infrared radiation emitted by the Earth/atmosphere system. Second, cirrus clouds cool the atmosphere by reflecting part of the incoming solar radiation back into space. The contribution of each effect and the net effect on the radiative forcing depends strongly on cirrus cloud optical properties, altitude, vertical and horizontal coverage (Liou 1986, Kienast-Sjögren et al. 2016). Therefore, understanding their properties is critical to determine their impact on planetary albedo and greenhouse effects (Barja and Antuña, 2011, Boucher et al., 2013). Also, tropical cirrus clouds could influence the vertical distribution of radiative heating in the tropical tropopause layer (e.g., Yang et al., 2010b; Lin et al., 2013). Noticeably, it has been shown that an accurate representation of the cirrus vertical structure in cloud radiative studies improved the results of these calculations (Khvorostyanov and Sassen, 2002; Hogan and Kew, 2005; Barja and Antuña, 2011). Recent research also shows that an increase of stratospheric water vapor is linked mainly to the occurrence of cirrus clouds in the tropical tropopause layer (TTL) (Randel and Jensen, 2013). Finally, measurements of the properties of cirrus clouds at different geographical locations are of utmost importance, potentially allowing for improvements in numerical model parameterizations and, thus, reducing the uncertainties in climatic studies.

Ground-based lidars are an indispensable tool for monitoring cirrus clouds, particularly those cirrus clouds with very low optical depth, which are undetectable for cloud radars (Comstock et al., 2002) or for passive instruments (e.g., Ackerman et al., 2008). For this reason, several studies with ground-based lidars have reported the characteristics of cirrus clouds around the globe during the last decade. There are some long-term studies reporting climatologies at midlatitudes (eg. Sassen and Campbell, 2001; Goldfarb et al., 2001; Giannakaki et al., 2007; Hoareau et al., 2013; Kienast-Sjögren et al. 2016) and tropical regions (eg. Comstock et al., 2002; Cadet et al., 2003; Antuña and Barja, 2006; Seifert et al., 2007; Thorsen et al., 2011; Pandit et al., 2015). Table 1 shows an overview of these studies with different values for cirrus clouds characteristics in diverse geographical regions. There are also some short-term reports on cirrus clouds characteristics during measurement campaigns at midlatitudes (e.g. Immler and Schrems, 2002a) and tropical latitudes (Immler and Schrems, 2002b, Pace et al., 2003 and references therein). Additionally, satellite-based lidar measurements have been used to investigate the global distribution of cirrus characteristics (eg. Nazaryan et al., 2008; Sassen et al., 2009; Sassen et al., 2009; Wang and Dessler 2012, Jian et al., 2015). Characteristics of tropical and subtropical cirrus clouds have similar

$$xy = yx$$

75 geometrical values and they occur at higher altitudes than those at midlatitudes. However, the frequencies  
 76 of occurrence of cirrus cloud types differ significantly between different locations.  
 77 Reports on cirrus cloud measurement over tropical rain forests like in Amazonia are scarce. Just a few  
 78 global studies with satellite instruments include these regions, and they do not provide information on the  
 79 ~~daily~~ <sup>diurnal</sup> cycle. There are also a few studies focused on deep convection in Amazonia that reported cirrus  
 80 clouds (eg. Machado et al., 2002; Hong et al., 2005; Wendisch et al., 2016), but no lidar measurements  
 81 were used. Baars et al. (2012) focused on aerosol observations with a ground-based Raman lidar, and thus  
 82 report exemplary only one cirrus cloud case that was observed between 12 km and 16 km height on  
 83 September 11, 2008 during <sup>an</sup> ~~the~~ 11-months measurement period in 2008. Barbosa et al. (2014) describe a  
 84 week of cirrus cloud measurements performed from 30 August to 6 September 2011 during an intensive  
 85 campaign for calibration of the water vapor channel of the UV Raman lidar, which is also used in this  
 86 study. Cirrus clouds during that period were present in 60% of the measurements. Average base and top  
 87 heights were 11.5 km and 13.4 km, respectively, and average maximum backscatter occurred at 12.8 km.  
 88 Most of the time, two layers of cirrus clouds were <sup>present</sup> ~~actually~~ found.  
 89 From the above discussion, the importance of continuous and long-term observations of tropical cirrus  
 90 clouds is evident. In the present study, we use one year of ground-based lidar measurements (July 2011 to  
 91 June 2012) at Manaus, Brazil to investigate the seasonal and daily cycles of geometrical (cloud top and  
 92 base altitude) and optical (cloud optical depth and lidar ratio) properties of cirrus over a tropical rain  
 93 forest site. In section 2, a description of the Raman lidar system, dataset, processing algorithms and site  
 94 are given. The results and discussion are presented in section 3. We close this paper with concluding  
 95 remarks in section 4.

## 96 2. Instrumentation, dataset and algorithms.

### 97 2.1. Site and instrument description

98 The ACONVEX (Aerosols, Clouds, cONvection EXperiment) or T0e (nomenclature of the  
 99 GoAmazon2014/15 experiment, Martin et al. 2016) site is located up-wind from Manaus-AM, Brazil, at  
 100 2.89° S and 59.97° W, in the central part of the Amazon Forest, as shown in the satellite image of Figure  
 101 1. Atmospheric observations at this site began in 2011 with the objective to operate a combination of  
 102 several instruments for measuring atmospheric humidity, clouds and aerosols as well as processes which  
 103 lead to convective precipitation (Barbosa et al., 2014).  
 104 As with most tropical continental sites, the diurnal cycle of precipitation is strong with a late afternoon  
 105 peak (Adams et al., 2013). The precise definition of the climatological seasons varies among authors (e.g.  
 106 Machado et al., 2004, Arraut et al., 2012, Tanaka et al., 2014), however, deep convection is a  
 107 characteristic of the region ~~during~~ <sup>respectively</sup> all year. For our site and period of study, we considered a wet (Jan-  
 108 Apr), a dry (Jun-Sep), and a transition (Mar, Oct-Dec) season. Convection is more active during the wet  
 109 season, when the intertropical convergence zone (ITCZ) influences the region. As the ITCZ moves  
 110 northward during the months of the dry month, ~~the~~ convective activity decreases.  
 111 The lidar system (LR-102-U-400/HP, manufactured by Raymetrics Advanced Lidar Systems) operates in  
 112 the UV at 355 nm. Three channels detect the elastically backscattered light at 355 nm as well as the

<sup>↑</sup>  
 Ultraviolet (UV)



113 Raman-scattered light of nitrogen (387 nm) and water vapor (408 nm), simultaneously in analog and  
114 photon-counting modes. The system is tilted by 5° from the zenith to avoid specular reflection of  
115 horizontally-oriented ice crystals (e.g., Westbrook et al., 2010). It is automatically operated 7 days a  
116 week, only being closed between 11 am and 2 pm local time (LT is -4 UTC) to avoid the sun crossing the  
117 field of view. Detailed information about the lidar system and its characterization are given by Barbosa et  
118 al. (2014). To retrieve the particle backscatter and extinction profiles from the lidar signal, ~~the~~  
119 temperature and pressure profiles were obtained from ~~the~~ radio soundings launched at 0 and 12 UTC from  
120 the Ponta Pelada Airport, located 28.5 km to the South (3.14°S, 59.98°W) of the experimental site.

## 121 2.2. Datasets

122 The lidar dataset used in the present study comprises measurements recorded between July 2011 and June  
123 2012. A total of 36,597 5-minute profiles were analyzed, corresponding roughly to 1/3 of the maximum  
124 possible number of profiles during 1 year.  
125 For the long-term analysis, winds were obtained from the ERA Interim reanalysis (Dee et al., 2011) of  
126 European Center for Midrange Weather Forecast (ECMWF) with spatial resolution of 0.75° and temporal  
127 resolution of 6 h. The tropopause altitudes were calculated using ERA Interim temperature profiles  
128 interpolated to the measurement time of each cirrus layer observation. We followed the definition of the  
129 World Meteorological Organization (IMV WMO, 1966), i.e. *"the lowest level at which the lapse rate  
130 decreases to 2 °C km<sup>-1</sup> or less, provided that the average lapse rate between this level and all higher  
131 levels within 2 km does not exceed 2 °C km<sup>-1</sup>"*. We further assumed the lapse rate to vary linearly with  
132 pressure (McCalla, 1981), and the exact altitude where  $\Gamma=2$  °C km<sup>-1</sup> (i.e. the tropopause) was found by  
133 linearly interpolating between the closest available pressure levels. Precipitation was obtained from  
134 TRMM (Tropical Rainfall Measuring Mission) version 7 product 3B42 (Huffman et al., 2007) with 0.25°  
135 and 3 h of spatial and temporal resolution, respectively. Back trajectories were calculated using the  
136 HYSPLIT model (Stein et al., 2015) forced by meteorological fields from the US National Oceanic and  
137 Atmospheric Administration (NOAA) Global Data Assimilation System (GDAS), available at 0.5 degree  
138 resolution.

## 139 2.3. Cirrus cloud detection algorithm.

140 We used an automatic algorithm for the detection of the cloud base, the cloud top and the maximum  
141 backscattering heights, based on Barja and Aroche (2001). The algorithm is explained in detail in Barbosa  
142 et al. (2014) and is in here only described briefly. Basically, it assumes a monotonically decreasing  
143 intensity of the lidar signal with altitude in a clear atmosphere and searches for significant abrupt changes.  
144 These abrupt changes are marked as a possible cloud base. Examining the signal noise, each true cloud  
145 base is discriminated. Then, the lowest altitude above cloud base with signal lower than that at cloud base  
146 and corresponding to a molecular gaseous atmosphere is determined as the cloud top. When more than  
147 one layer is present in the same profile, and their top and base are separated more than 400 m, they are  
148 considered as individual clouds. Figure S.2 gives an example of cloud detection. Barbosa et al. (2014)  
149 provide also information on the discrimination of false ~~alarms~~ <sup>positives</sup> and distinguishing aerosols from thin cloud  
150 layers. After obtaining the base, top and maximum backscatter heights, the corresponding cloud



151 temperatures are obtained from the nearest radiosonde. A detected high cloud is classified as a cirrus  
152 cloud if the cloud top temperature is lower than  $-37^{\circ}\text{C}$  (Sassen and Campbell, 2001; Campbell et al.,  
153 2015). These temperatures are typically found at about 10.5 km height over Amazonia.

#### 154 2.4. Frequency of Occurrence and Sampling Issues

155 In a simplified manner, the frequency of occurrence would just be the ratio of the number of profiles with  
156 cirrus clouds to the total number of profiles. However, while one might be sure when a cirrus was <sup>cloud</sup>  
157 detected in a given profile, there is no certainty of its presence when the profile has a low signal-to-noise  
158 ratio or when there is no measurement available. Sampling cirrus clouds with a ground-based profiling  
159 instrument <sup>can</sup> might be problematic, particularly for the calculation of the temporal frequency of occurrence,  
160 due to the obscuration by lower clouds, or availability of measurements, which might introduce sampling  
161 biases (Thorsen et al., 2011).

162 To avoid these sampling issues, we use an approach similar to the conditional sampling proposed by  
163 Thorsen et al. (2011) and Protat et al. (2014). First, we recognize that the presence of cirrus clouds is  
164 rather independent of low-level liquid water clouds that can fully attenuate the laser beam, and  
165 independent of instrumental issues that might restrict measurement time. Hence, the best estimate of the  
166 true frequency of occurrence is the ratio of the number of profiles with cirrus, by the number of profiles  
167 where cirrus could have been detected.

168 These <sup>good</sup> profiles are identified as follows. The noise in each clear-sky bin follows a Poisson  
169 distribution and is evaluated as the square root of the signal. The signal-to-noise ratio (SNR) is defined as  
170 the background corrected signal divided by the noise, similarly <sup>for</sup> to Heese et al. (2010). Profiles are  
171 selected if a clear-sky SNR higher than 1.0 is found at 16 km, considering 7.5 m vertical resolution. Note  
172 that this is not the SNR of the cirrus cloud (cirrus – molecular / noise), which typically ranges from 6 to  
173 36. The threshold was obtained from a performance evaluation of the detection algorithm. Using  
174 simulations, we varied cloud thickness (15 m to 4.5 km), cloud backscatter coefficient (1 to  $10\text{ Mm}^{-1}\text{ sr}^{-1}$ )  
175 and SNR (1 to 50). We found that our algorithm detects 99% of cirrus clouds with  $\text{COD} > 0.005$ . In other  
176 words, given <sup>the</sup> typical cirrus cloud optical depths, the used threshold implies a sufficiently high SNR at  
177 cloud top for applying the transmittance method (described in section 2.5).

178 From <sup>the</sup> analysis of the available profiles, 16,025 were found to satisfy these criteria (see Table 2). July,  
179 August and September, the driest months, show the highest fraction of profiles with good SNR, while the  
180 wettest months have the lowest fraction of lidar profiles with good SNR (see figure S.1). To avoid  
181 introducing biases from the different sample sizes in different months, the frequency of occurrence for the  
182 year is calculated as the average frequency of occurrence for each season. The frequency for each season,  
183 in turn, is calculated from the frequency of each month. Finally, the frequency for each month is  
184 calculated by averaging over the mean diurnal cycles (i.e. mean of hourly means), because there are more  
185 profiles with good SNR during night compared to daytime.

#### 186 2.5. Cloud Optical Depth, backscattering coefficient and lidar ratio

187 <sup>The</sup> attenuation of the lidar signal by cirrus clouds can be obtained using the ratio of the range-corrected  
188 signal at the top and at the cloud base as described in Young (1995):

$$\frac{S(z_t)}{S(z_b)} = \frac{\beta(z_t)}{\beta(z_b)} e^{-2 \int_{z_b}^{z_t} \alpha_p(z') dz'} e^{-2 \int_{z_b}^{z_t} \alpha_m(z') dz'} , \quad (1)$$

where  $z_b$  and  $z_t$  are the base and top height of a cirrus layer, and  $S(z) = P(z)z^2$  is the range corrected signal.  $\beta(z)$  and  $\alpha(z)$  are the volumetric backscattering and extinction coefficients, respectively, and each is the sum of a molecular (sub index m) and a particle (sub index p) contribution. Volumetric backscattering and extinction profiles from molecules were derived following Bucholtz (1995). Assuming a negligible aerosol contribution in the atmospheric layers just below and above the cirrus clouds (Young, 1995), we can express the transmittance factor of the lidar equation due to the cirrus layer,  $T^{\text{cirrus}}$ , as

$$T^{\text{cirrus}} = e^{-2 \int_{z_b}^{z_t} \alpha_p(z') dz'} = \frac{S(z_t) \beta(z_b)}{S(z_b) \beta(z_t)} e^{2 \int_{z_b}^{z_t} \alpha_m(z') dz'} , \quad (2)$$

and the cirrus optical depth (for an example, see Figure S.2),  $\tau^{\text{cirrus}}$ , as

$$\tau^{\text{cirrus}} = \int_{z_b}^{z_t} \alpha_p(z') dz' = -\frac{1}{2} \ln(T^{\text{cirrus}}) . \quad (3)$$

The accuracy of this calculation depends mainly on the SNR at the cirrus cloud altitude. However, when the lidar signal is completely attenuated by the cirrus cloud (i.e. the transmission factor approaches zero) it is impossible to obtain the true values of the cirrus top altitude and optical depth. The retrievals, in these cases called apparent values, are necessarily underestimated and were not included in our analysis (see Table 2).

The backscattering coefficients of cirrus clouds were determined by the Fernald-Klett-Sasano method (Fernald et al., 1972; Klett, 1981; Sasano and Nakane, 1984) for each 5-min averaged profile <sup>that have</sup> <sup>having</sup> cloud and satisfied the conditions discussed in the previous section. For retrieving <sup>the</sup> extinction, the Klett method requires a predetermined value for the layer-mean lidar ratio (LR), which is the ratio between the extinction and backscattering coefficient. Then, integrating the extinction coefficient from the cloud base to cloud top, the cirrus cloud optical depth is obtained ( $\tau_{\text{Klett}}^{\text{cirrus}}$ ). Following Chen et al. (2002), we estimated the value of LR for every cloud profile by iterating over a range of values of LR and comparing the values of  $\tau_{\text{Klett}}^{\text{cirrus}}$  with the independent value of the cirrus optical depth obtained from the transmittance method described above ( $\tau^{\text{cirrus}}$ ). The cirrus mean lidar ratio is the one that minimizes the residue:  $R(S) = (\tau_{\text{Klett}}^{\text{cirrus}} - \tau^{\text{cirrus}})^2$ . We use the approach of Chen et al. (2002) instead of the Raman method (Ansman et al., 2002) because our instrument can only detect the Raman scattered light at nitrogen during nighttime as Raman scattering is very weak compared to the elastic scattering. Moreover, the Raman results are very noisy even during nighttime and, by analyzing simulated lidar profiles (not shown), we found that for the given setup of our study <sup>(24/7 analysis of 5-min profiles)</sup> a more precise and accurate cirrus layer-mean LR can be obtained with <sup>the et al. (2002)</sup> Chen's method.

The Klett method assumes single scattering, but eventually <sup>apparent</sup> the received photons could have been scattered by other particles multiple times before reaching the telescope. This effect, named multiple scattering, increases the laser transmittance and decreases the <sup>corresponding</sup> real extinction coefficient values. Inversion of uncorrected signals could bias the extinction, and hence the COD and LR, typically by 5-30% (Thorsen and Fu, 2015). This is particularly important at UV wavelengths, for which a much stronger forward scattering and therefore larger amounts of multiple scattering occur compared to the visible or infrared wavelengths. For this reason, we refrain from applying empirical correction formulas (e.g. such as eq. 10 in Chen et al., 2002), and <sup>instead</sup> we perform a full treatment of multiple scattering following the model of Hogan



$x_2 = y^x$

worries me slightly,  
but small concern  
may want to check  
out

Hayfield  
et al  
2014  
JAS  
to see how  
they  
compare?

227 (2008) that was also used by Seifert et al. (2007) and Kienast-Sjögren et al. (2016). In our case, we  
228 assumed the effective radius of ice crystals to vary with temperature according to a climatology of aircraft  
229 measurements of tropical cirrus data (Krämer et al., 2016a, 2016b). The full treatment corrects the  
230 retrieved LR by about 40%, from  $16.8 \pm 5.8$  sr (uncorrected) to  $23.6 \pm 8.1$  sr, while Chen's approach  
231 would only correct it to  $20.2 \pm 7.0$  sr. In the following sections, all cirrus optical properties (lidar ratio,  
232 extinction coefficient, and optical depth) derived in the frame of this study were corrected for multiple-  
233 scattering.

### 234 3. Results and discussion.

#### 235 3.1. Frequency of cirrus cloud occurrence.

236 A total of 11,252 lidar profiles were recorded with the presence of cirrus clouds, yielding an average  
237 temporal frequency of cirrus cloud occurrence of 73.8 % from July 2011 to June 2012. Figure 2 shows the  
238 monthly frequency of occurrence of cirrus clouds, with the statistical error, and the precipitation in central  
239 Amazonia. There is a well-defined seasonal cycle, with maximum values from November to April,  
240 reaching 88.1 % during the wet season, and a minimum value in August during the dry season (59.2 %),  
241 but with frequencies not lower than a rather high amount of 50 % (see Table 2). Moreover, the mean  
242 monthly cirrus cloud frequency follows the same seasonal cycle as the accumulated precipitation, which  
243 responds to the seasonal changes of the ITCZ, and is higher from January to April, and lower from June  
244 to September (Machado et al., 2002; 2014). The mean cirrus frequencies during the wet months are higher  
245 by a statistically significant amount than during dry months (notice the small standard deviation of the  
246 mean despite the high variability). This result and the lack of the other possible formation mechanisms  
247 proposed in the literature (Sassen et al., 2002) suggest that deep convection is the main formation  
248 mechanism for cirrus clouds in central Amazonia. Deep convective clouds generate cirrus clouds when  
249 winds in the upper troposphere remove ice crystals of the top of the large convective column, generating  
250 the anvil cloud. The anvil cloud remains even after the deep convective cloud dissipates and persists from  
251 0.5 up to 3 days (Seifert et al, 2007).

local

252 To further investigate the role of deep convection as the main formation mechanism, the high-altitude  
253 circulation and the spatial distribution of precipitation were studied. The mean wind field at 150 hPa,  
254 approximately the mean cirrus top-cloud altitude (14.3 km, see Table 3), and the accumulated  
255 precipitation are shown in Figure 3. The study period was divided into wet (January, February, March and  
256 April), dry (June, July, August and September) and transition (May, October, November and December)  
257 periods, based on the accumulated precipitation. During the wet months, the South American monsoon is  
258 prevalent, and associated rain amounts range from 8 to 14 mm/day, with monthly accumulates of about  
259 300 mm. Winds at 150 hPa blow from the southeast at about 6 m/s. During the dry period, convective  
260 activity moved to the north toward Colombia and Venezuela and the 150 hPa air flow is from the west,  
261 also at about 6 m/s, thus allowing cirrus clouds to be advected by 520 km or  $4.5^\circ$  per day. As previous  
262 studies reported that tropical cirrus could be transported by thousands of kilometers (e.g. Fortuin et al.,  
263 2007), 24-h back-trajectories were calculated to investigate the possible origin of the observed clouds.  
264 These are shown in the right panels of Figure 3, where one trajectory was calculated for each cirrus layer



265 detected, with the arrival height set to the height of top of the cirrus layer. Most of the trajectories are  
 266 directed to the regions of maximum accumulated precipitation (left panel), which are much closer to the  
 267 site during the wet ( $\sim 5^\circ$ ) than ~~during the~~ <sup>likeliest</sup> dry ( $\sim 10^\circ$ ) season. This gives further evidence that cirrus clouds  
 268 observed in central Amazonia are ~~detained~~ <sup>likely</sup> anvils from tropical deep convection. The backward  
 269 trajectories also reveal that the high-altitude circulation is quite variable. Indeed, many backward  
 270 trajectories do not follow the average wind pattern and seem to point in the opposite direction of ~~the~~  
 271 precipitation, particularly during the dry season. One should note, however, that central Amazonia still  
 272 receives about 100 mm per month of precipitation in the dry season (reddish colors around the site, Figure  
 273 3) and most of it comes from mesoscale convective systems (Machado et al., 2004; Burleyson et al.,  
 274 2016). Hence, during the dry season, there is a mixture of ~~near-by~~ <sup>locally-</sup> produced and long-range transported  
 275 cirrus, in contrast to the wet season, when there is always near-by convection.  
 276 The diurnal cycle of ~~the frequency of~~ <sup>the frequency of</sup> cirrus clouds, shown in Figure 4, has also a close relation with the  
 277 convective cycle. The frequency of occurrence, for the overall period or any season, exhibits a minimum  
 278 between 10 and 14 hours local time (LT). Maximum values are found between 17 and 18 LT, in the late  
 279 afternoon, when values are slightly higher than in the morning. This diurnal variation follows the diurnal  
 280 cycle of convection documented in the literature (e.g. Machado et al., 2002; Silva et al., 2011, Adams et  
 281 al. 2013), as also shown in Figure 4 as the diurnal cycle of precipitation averaged over an area of  $2^\circ \times 2^\circ$   
 282 centered on the experimental site. ~~The~~ <sup>the</sup> maximum precipitation occurs between 13 and 18 LT, both ~~during~~  
 283 the dry and the wet seasons, which coincides with the increase in ~~the~~ <sup>in</sup> cirrus frequency. In Figure 4, a  
 284 smaller amplitude of ~~the~~ <sup>in</sup> cirrus frequency during the wet season ~~months~~ <sup>versus</sup> ~~than during the~~ dry season  
 285 ~~months~~ <sup>recommended</sup> is seen. This can be ~~understood~~ <sup>presumably</sup> by analyzing the maximum precipitation rates and the upper-  
 286 altitude circulation (see Figure 3). When the frequency of deep convection is greater (3 times more in the  
 287 wet season) and closer to the site ( $\sim 5^\circ$  in the wet and  $\sim 10^\circ$  in the dry), the cirrus clouds, which are long-  
 288 lived, get more evenly distributed during the day.  
 289 To verify that the lower cirrus cloud cover around noon was not related to a decrease in SNR and, hence,  
 290 a decrease in detection efficiency, we analyzed the frequency of occurrence for different cirrus types  
 291 (following Sassen and Cho, 1992). Opaque ( $COD > 0.3$ ), thin ( $0.3 > COD > 0.03$ ) and sub-visual cirrus  
 292 (SVC) clouds ( $COD < 0.03$ ) were considered. Their diurnal variation is also shown in Figure 4. The  
 293 frequency of occurrence of opaque cirrus has the larger amplitude, during both dry and wet seasons.  
 294 During the dry (wet) season, it increases from less than 5 % (20 %) to about 30 % (50 %) in the hours  
 295 following the precipitation maximum, 15 h to 19 h LT. The second larger diurnal variation corresponds to  
 296 the occurrence frequency of thin cirrus, which decreases after the sunrise from 30 % (50 %) to 20 % (30  
 297 %) during the dry (wet) season, and increase again during night time, when the opaque cirrus clouds are  
 298 dissipating. The SVC, whose detection could be biased by lower SNR, do not show a clear diurnal cycle.  
 299 Hence, the diurnal cycle of the frequency of occurrence of cirrus clouds in central Amazonia is likely a  
 300 result of the diurnal cycles of opaque and thin cirrus, which have a sufficiently high COD to not be  
 301 missed by the detection algorithm.

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### 3.2. Geometrical, optical and microphysical properties of cirrus clouds.

Table 2 shows column-integrated statistics of the properties of cirrus clouds during the one-year observational period also <sup>distributed by</sup> divided for the different seasons. On average, 1.4 layers of cirrus are present in each cloudy profile (1.25 during the dry, and 1.62 during the wet season). Column-integrated COD varies from  $0.25 \pm 0.45$  in the dry season to  $0.47 \pm 0.65$  in the wet season. The frequency of occurrence of opaque, thin and SVC column-integrated COD is 11.8 % (31.3 %), 23.9 % (37.9 %) and 23.3 % (18.3 %) respectively in the dry (wet) season. The maximum backscattering altitude does not show a seasonal cycle, and is on average  $13.4 \pm 2.0$  km (or  $-60 \pm 15$  °C).

As cirrus at different altitudes might have different origins and properties, it is more important to analyze the statistics based on the layers detected as shown in Table 3. The overall mean value for the cloud base altitude is  $12.9 \pm 2.2$  km, for the cloud top altitude,  $14.3 \pm 1.9$  km, and for the geometrical thickness,  $1.4 \pm 1.1$  km. The mean value of the cloud maximum backscattering altitude is  $13.6 \pm 2.0$  km. The differences between the mean values of the geometrical properties in the dry and wet seasons are not statistically significant, except for the thickness, which changes from 1.3 km to 1.5 km, respectively. These values are similar to those reported by Seifert et al. (2007) for the Maldives ( $4.1$  °N,  $73.3$  °E):  $11.9 \pm 1.6$  km (base),  $13.7 \pm 1.4$  km (top),  $1.8 \pm 1.0$  km (thickness),  $12.8 \pm 1.4$  km (max. backscatter) and  $-58 \pm 11$  °C (temperature at max. backscatter). Reports from subtropical regions also show similar values. Cadet et al. (2003) report for the Reunion Island ( $21$ °S,  $55$ °E) cirrus cloud base and top altitudes of 11 km and 14 km, respectively. Antuña and Barja (2006) report for a subtropical experimental site (Camagüey, Cuba,  $21.4$ ° N,  $77.9$ ° W) cirrus cloud base and top altitudes of 11.63 km and 13.77 km, respectively. On the other hand, Sassen and Campbell (2001) show mean values for midlatitude cirrus cloud base and top of 8.79 km and 11.2 km, respectively, which is lower than for tropical cirrus, and an average geometrical thickness of 1.81 km. Some cirrus cloud characteristics reported around the globe are shown in Table 1 for comparison.

The geometrical characteristics of the detected cirrus clouds were further examined by means of normalized histograms. Figure 5 shows the results for cloud base and top height, thickness and cloud optical depth. Histograms for the wet and dry season months reveal differences. The cloud base distribution (Figure 5a) is wider during the wet season. There are relatively more cirrus layers with cloud base below 12 km and above 16.5 km during the wet than during the dry season. Particularly, there is a peak centered at 16.5 km during wet months, which does not exist during the dry season months. The distribution of geometrical thickness (Figure 5b) shows more cirrus layers thicker than 2 km (and less thinner than that) in the wet season. The normalized histogram of COD (Figure 5d) shows relatively more cirrus layers with COD  $> 0.1$  in the wet season, and more with COD  $< 0.1$  in the dry season. The largest differences, however, are in the cirrus cloud top altitude distribution (figure 5c). It shows two peaks in the wet months, one centered at 14.25 km and second centered at 17.75 km. On the other hand, for dry months, there is only one peak centered at 15.75 km. These differences suggest different cirrus types with different origins.

Comstock et al. (2002) proposed two different types of cirrus clouds at Nauru Island in the tropical western Pacific with oceanic conditions: one type (laminar thin cirrus) with cloud base altitudes above 15 km and the other (geometrically thicker and more structured cirrus) with base altitudes below this

Average?  
Wow, that's high.  
absolute or relative?  
repeated?



342 value, with different characteristics. Liu and Zipser (2005) used TRMM Precipitation Radar (PR) dataset  
 343 to trace the deep convection and precipitation throughout the tropical zone, including oceans and  
 344 continents. The authors showed that only 1.38 % and 0.1 % of tropical convective systems, and  
 345 consequently their generated cirrus clouds reached 14 km and 16.8 km of altitude, respectively.  
 346 Considering these previous results, we suggest that the highest peak in wet months in cloud top  
 347 distribution originates from convection penetrating the tropopause, located at about 15.9-16.5 km, while  
 348 the lowest peak is the ceiling of most tropical convection. The single peak observed during the dry  
 349 months, in turn, originates from cirrus clouds transported <sup>by</sup> from large distances. Clouds generated by  
 350 convective systems can persist in the atmosphere from hours to days if they are slowly lifted (Ackerman  
 351 et al., 1988; Seifert et al., 2007). Clouds that ascended and are horizontally transported by long distances  
 352 are, in general, optically and geometrically thinner and found at higher altitudes in the troposphere. This  
 353 also explains why the geometrical thicknesses and optical depth are lower during the dry season months.  
 354 To investigate if the higher cirrus layers were indeed geometrically and optically thinner, a more in-depth  
 355 analysis of the vertical distribution was performed. Figure 6 shows two-dimensional histograms of cloud  
 356 optical depth and cirrus occurrence vertical distribution for the wet season months (top) and dry season  
 357 months (bottom). The right panels show the vertical distribution of the frequency of occurrence for the  
 358 three cirrus categories. During the wet months, there is more dispersion (wider range of COD for a fixed  
 359 altitude, and vice-versa) than in the dry months, which we speculate might be associated with the well-  
 360 documented variability in the intensity of deep convection in Amazonia (Machado et al., 2002; Adams et  
 361 al., 2009, 2013, 2015). Indeed, it is only during the wet season that a significant fraction of cirrus is found  
 362 above 16 km height, and they have a COD ranging from 0.001 to 0.02. Moreover, while the distribution  
 363 of opaque cirrus peaks at 12 km height in both seasons, thin cirrus and SVC shows a bimodal distribution  
 364 with the highest maxima above 14 km and 16 km respectively. This is associated with the overshooting  
 365 convection discussed above, which occurs mostly during the wet season (Liu and Zipser, 2005).  
 366 To investigate the role of the tropopause capping on the cirrus vertical development, its altitude was  
 367 calculated from the ERA Interim dataset for the observation time of each cirrus profiles (see section 2.2  
 368 and Figures S.3a and S.3b). The tropopause mean altitudes during the wet, transition and dry periods are  
 369  $16.5 \pm 0.2$  km,  $16.3 \pm 0.3$  and  $15.9 \pm 0.4$ , respectively. Therefore, a non-negligible fraction of the  
 370 observed cirrus during the wet and dry seasons (Figure 6) occurred likely above the tropopause. Figure 7  
 371 shows the distribution of the distance from the cloud top and bottom to the tropopause. About 7 % (19 %)  
 372 of the detected cirrus clouds have their cloud base (top) above the tropopause during the wet season, and  
 373 5 % (13 %) during the dry season. Most of the cirrus cloud tops are found right below the tropopause  
 374 inversion, except during the wet season when they are uniformly distributed from -2 km to +0.5 km,  
 375 which is associated with the variability in deep convection intensity as discussed above. During the dry  
 376 season, on the other hand, deep convection overshooting occurs primarily north of the equator (Figure 2  
 377 from Liu and Zipser, 2005). These cirrus that ~~has~~ formed around the tropopause cannot last for a long  
 378 time, as they cannot be adiabatically lifted above the tropopause inversion (Jensen et al., 1996).  
 379 Therefore, they cannot be transported over long distances and do not reach the measurement site, hence  
 380 there is only one maximum near 15 km in the distribution of cloud tops, which is just below the  
 381 tropopause.

height

what about  
TTL  
Cirrus?

TTL?

define  
??



382 The classification of cirrus clouds following Sassen and Cho (1992) shows that 41.6 % of the cirrus  
383 clouds measured in our experimental site are subvisible ( $\tau < 0.03$ ), 37.8 % are thin cirrus ( $0.03 < \tau < 0.3$ )  
384 and 20.5 % are opaque cirrus ( $\tau > 0.3$ ). Table 3 shows these values for each season. SVC clouds have the  
385 highest (lower) fraction during dry (wet) months. Opaque clouds have the highest (lowest) fraction during  
386 wet (dry) months, which is expected, as there is a predominance of newly generated clouds by deep  
387 convection.

388 This large fraction of optically thin and subvisible cirrus clouds over Amazonia present a challenge for  
389 using passive remote sensing from space, such as MODIS. As mentioned by Ackerman et al. (2010), thin  
390 cirrus clouds are difficult to detect because of insufficient contrast with the surface radiance. MODIS only  
391 detects cirrus with optical depth <sup>typically</sup> higher than 0.2 (Ackerman et al., 2008). Therefore, the MODIS's cloud-  
392 mask does not include 71 % of cirrus clouds over Amazonia, and likewise, their estimation of aerosol  
393 optical depth might be contaminated with these thin cirrus. Aerosol optical depth measurements from  
394 AERONET can also be contaminated with thin cirrus clouds. Chew et al. (2011), for instance, estimated  
395 that the fraction of contaminated measurements of AERONET AOD in Singapore (1.5° N, 103.7° E) is  
396 about 0.034 to 0.060. The determination of the actual contamination of MODIS and AERONET aerosol  
397 products for Amazonia by thin cirrus will be the subject of a forthcoming study.

398 The different types of cirrus clouds measured in central Amazonia, with different formation mechanisms,  
399 optical depths and altitude ranges are expect to be composed of ice crystals of different shapes. One way  
400 to gain information on the crystal habits is to compute the lidar-ratio (Sassen et al., 1989). As explained in  
401 section 2, we are able to <sup>estimate</sup> find the average lidar ratio for the detected cirrus cloud layers in each profile  
402 using an interactive approach instead of explicitly calculating the extinction from the Raman signal,  
403 which would be available only during night-time.

404 Average values are given in Table 3 for all cirrus, and for each category. A mean value of  $23.9 \pm 8.0$  (std)  
405 sr was obtained for the whole period and the variation is less than 1.5 sr for the different seasons, i.e., it  
406 does not show a seasonal cycle. For opaque, thin and SV cirrus the means are  $25.7 \pm 6.3$  sr,  $22.8 \pm 7.9$  sr  
407 and  $21.6 \pm 8.4$  sr, respectively. Pace et al., (2003) found a mean value of lidar ratio of 19.6 sr for the  
408 tropical site of Mahé, Seychelles. Seifert et al.(2007), also for tropical regions, report values close to  
409 32 sr. Platt and Diley (1984) reported the value of 18.2 sr with an error of 20%. For the other latitudes,  
410 examples are given in Table 1. We note, however, that the lidar ratio may vary greatly depending on the  
411 altitude and composition of cirrus clouds (Goldfarb et al., 2001), but also on the correction for multiple  
412 scattering (Platt, 1981; Hogan, 2008). The latter depends on the ice crystals effective radius, and the  
413 associated uncertainty can range from 20 to 60 % (Wandinger, 1998).

414 Although the mean LR for all seasons and categories are similar, their statistical distribution might yet  
415 reveal differences. Figure 8 shows the histograms of lidar ratio corrected for multiple-scattering for the  
416 different seasons (top) and for the different categories (bottom). For all seasons, the most frequent lidar  
417 ratios are between 18 sr and 28 sr. There are notable differences only for different cirrus categories. The  
418 opaque cirrus distribution has a peak at 25 sr, while thin cirrus has its peak at about 21 sr, and SVC at  
419 about 15 sr, with a secondary peak at 44 sr.

420 As the cirrus properties are expected to depend on altitude (e.g., Goldfarb et al., 2001), we examine the  
421 dependence of the lidar ratios with the cirrus cloud top temperature (Figure 9). The plots show the mean,

2 microphysical?

Right... in Campbell  
et al (2016) we saw a  
similar distribution, which  
we thought was skewed

by  
sample  
bias

← MCF! If you're interested, look at JTECH Early online release for new paper by our group from Marguis et al. on C<sub>2</sub>-contamination of tropical SST retrievals!

the median, and the interquartile distance. A slight increase in the lidar ratio values from 20 sr to 28 sr for a decrease in temperature from -40 to -55 °C can be noticed during the dry period. During the wet period, the lidar ratio values are between 18 sr and 28 sr in all temperature intervals. Seifert et al. (2007) and Pace et al. (2003) both show the same temperature dependence of the lidar ratio, but with different mean values of the lidar ratio. This behavior is an indication of a slight variation in the microphysical characteristics of the observed clouds.

#### 4. Conclusions.

One year of ground-based lidar measurements <sup>collected</sup> performed between July 2011 and June 2012 were used to investigate the geometrical and optical properties of cirrus clouds in central Amazonia. An algorithm was developed to search through this dataset with high vertical and temporal resolution and to automatically <sup>absolute</sup> find clouds, calculate particle backscatter, and derive optical depth and lidar ratio. The frequency of cirrus cloud occurrence during the observation period was 73.8 %, which is higher than reported previously in the literature for other tropical regions. Cirrus frequency reached 88.1 % during the wet months (January, February, March and April), but decreased to 59.2 % during the dry months (June, July, August, and September). Analysis of high-level circulation and precipitation during the wet months indicate that near- <sup>locally-</sup> by deep convection was likely the main source of these cirrus. Whilst during the dry period, there was a mixture of <sup>transported</sup> near-by produced and advected clouds. Moreover, we found that the diurnal cycle of the frequency of occurrence of opaque and thin cirrus shows a minimum around 12h LT and a maximum around 18h LT, following the diurnal cycle of the precipitation for both seasons.

The geometrical, optical and microphysical characteristics of cirrus clouds measured in the present study were consistent with other reports from tropical regions. The mean values were  $12.9 \pm 2.2$  km (base),  $14.3 \pm 1.9$  km (top),  $1.4 \pm 1.1$  km (thickness), and  $0.25 \pm 0.46$  (optical depth). Cirrus clouds were found at temperatures down to -90 °C. 6 % (16 %) of the observed cirrus had their base (top) above the tropopause level or in the tropical tropopause layer.

By simultaneously analyzing cloud altitude and COD, it was found that cirrus clouds observed during the dry season months are optically <sup>thinner</sup> thinner and lower in altitude than those during the wet period. During the wet season months, there is a wider range of COD for a fixed altitude, and vice-versa, which is associated with the variability in the intensity of deep convection in Amazonia. The vertical distribution of the frequency of occurrence of the detected clouds shows a bimodal distribution for thin and SV cirrus during the wet season, which originates from overshooting convection.

For the first time, the lidar ratio of cirrus clouds was obtained for the Amazon region. The mean lidar ratio, <sup>corrected</sup> corrected for multiple-scattering, was  $23.6 \pm 8.1$  sr, in agreement with other reports from the tropical regions. The statistical distribution of lidar ratios measured during the different seasons is the same, and they also do not vary with the temperature (altitude) of the <sup>thin</sup> cirrus clouds, indicating that these clouds are well mixed in the vertical. <sup>thicker</sup> It was observed, however, that the distributions of the lidar ratio for different cirrus categories are quite different. They are more skewed towards lower lidar ratios for smaller COD. From all cirrus clouds observed, 41.6 % were classified as subvisible (COD < 0.03), 37.8 % as thin (0.03 < COD < 0.3) and 20.5 % as opaque (COD > 0.3). During the dry months, subvisible cirrus clouds reached a maximum frequency of occurrence of 46 %, while opaque cirrus have their maximum during



461 the wet season months (25.2 %). These values are characteristic for the region under study and somewhat  
462 different from other tropical regions. Thus, central Amazonia has a high frequency of cirrus clouds in  
463 general, and a large fraction of subvisible cirrus clouds. Therefore, the aerosol optical depth determined  
464 by Sun photometers and satellite based sensors in this region might be contaminated by the presence of  
465 these thin clouds. Future work must be conducted in order to evaluate how large this contamination might  
466 be over Amazonia.

YEP!

GREAT  
revision

== 11  
cheers..

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Tables:

Table 1. Summary of some recent cirrus cloud studies based on at least a few months of ground-based lidar observations in the tropics and mid-latitudes. The first columns show the period of study and laser wavelength (nm) for each site location, for which more than one study might be available. The cirrus characteristics are those reported by the different authors, which might include: base and top height (km), thickness (km), base and top temperature (°C), frequency of occurrence (%) and lidar-ratio (sr).

Measurement site	Location	Period of study	Wavelength [nm]	Average values							LR[sr]	
				Height [km]		Temp. [°C]		Frequency, [%]		SVC		Thin
				Base	Top	Thick.	Base	Top	SVC			
Salt Lake City, Utah, USA	40.8°N 111.8°W	1986 to 1996	694	8.8	11.2	1.8	-34.4	-53.9	50	-	Sassen and Campbell (2001)	
Haute Provence, France	43.9°N 5.7°E	1997 to 2007	532/1064	9.3	10.7	1.4			38		Goldfarb et al. (2001)	
Thessaloniki, Greece	40.6°N 22.9°E	2000 to 2006	355/532	8.6	11.7	2.7	-38	-65		57	30	Hoareau et al. (2013)
			2									Giannakaki et al. (2007)
Seoul, South Korea	37°N, 127°E	2006 to 2009	532/1064	8.8	10.6						20	Kim et al. (2009)
Buenos Aires, Argentina	34.6 °S, 58.5 °W	2001 to 2005	532	9.6	11.8	2.4		-64.5				Lakkis et al.(2008)
Reunion Island	21°S, 55°E	1996 to 2001	532	11	14				65		18.3	Cadet et al. (2003)
Camagüey, Cuba	21.4° N, 77.9° W	1993 to 1998	532	11.6	13.8				25		10	Antuña and Barja, (2006)
Gadanki, India	13.5° N, 79.2° E	1998 to 2013	532	13.0	15.3	2.3		-65	52	36	25	Pandit et al., (2015)
Hulule, Maldives	4.1°N, 73.3°E	1999, 2000	532	11.9	13.7	1.8	-50	-65	15	49	32	Seifert et al. (2007)
Mahé, Seychelles	4.4 °S, 55.3 °E	Feb-Mar 1999	532			0.2-2.0					19	Pace et al., (2003)
Nauru Island	0.5 °S, 166.9 °E	Apr-Nov 1999	532	~14	~16							Comstock et al. (2002)

Table 2. Summary of column-integrated statistics for the total time of observation, as well as for the wet, transition and dry seasons. Frequency of occurrence is calculated using a conditional sampling to avoid biases (session 2.4). Mean cirrus cloud properties and standard deviation of the sample (in parenthesis) are shown. The standard deviations of the mean can be calculated and used to determine if seasonal differences (wet-dry) of the mean values are statistically significant to the 95% confidence level (indicated as \*). Geometrical properties are not given because most cloud profiles have more than one layer of cirrus. Lidar ratio is calculated as a column average.

	<b>Total</b>	<b>Wet</b>	<b>Transition</b>	<b>Dry</b>
Observation time [%] <sup>a</sup>	37.4	41.5	21.9	48.9
N. prof. measured <sup>b</sup>	36844	13828	7423	15593
N. prof. used in analysis <sup>c</sup>	16025	3458	2099	10468
N. prof. discarded for apparent top <sup>d</sup>	476	223	148	105
Frequency of Occurrence [%]*	73.8	88.1	74.2	59.2
N. prof. w/ cirrus	11252	3145	1706	6397
Frequency of Occurrence, Opaque [%]*	22.6	31.3	24.6	11.8
N. prof. w/ cirrus, Opaque	3327	1316	610	1401
Frequency of Occurrence, Thin [%]*	32.8	37.9	36.5	23.9
N. prof. w/ cirrus, Thin	4577	1224	798	2555
Frequency of Occurrence, SVC [%]*	18.3	18.7	13.0	23.3
N. prof. w/ cirrus, SCV	3322	603	296	2423
Cloud Optical Depth*	0.35 (0.55)	0.47 (0.65)	0.40 (0.57)	0.25 (0.45)
Max Backscatter Altitude [km]*	13.4 (2.0)	13.4 (2.2)	13.3 (2.2)	13.6 (1.7)
Temperature Max. Back. Alt. [°C]*	-60 (15)	-60 (16)	-59 (17)	-62 (13)
Lidar Ratio [sr]* <sup>e</sup>	23.6 (8.1)	22.8 (8.0)	22.8 (7.8)	24.6 (7.7)
Num. of cirrus layers per cloud prof.	1.41 (0.63)	1.62 (0.77)	1.61 (0.67)	1.25 (0.48)

<sup>a</sup> Fraction of observation time to total possible time (21h per day)

<sup>b</sup> Total number of profiles measured, i.e. not screened for low clouds or precipitation

<sup>c</sup> Refers to the number of 5-min profiles with high enough SNR (section 2.4)

<sup>d</sup> Number of profiles with apparent cirrus top, considering only good profiles

<sup>e</sup> All layers in the same profile share the same average LR



Table 3. Summary of layer-statistics for the total time of observation, as well as for the wet, transition and dry seasons. Mean cirrus cloud properties and standard deviation of the sample (in parenthesis) are shown. The standard deviations of the mean can be calculated and used to determine if seasonal differences (wet-dry) are statistically significant to the 95% confidence level (indicated as \*). Lidar ratio is calculated as a column average.

<i>All Layers</i>	<b>Total</b>	<b>Wet</b>	<b>Transition</b>	<b>Dry</b>
Num. of cirrus layers	15824	5096	2739	7989
Base Altitude [km]*	12.9 (2.2)	12.8 (2.4)	12.6 (2.3)	13.0 (1.9)
Top Altitude [km]	14.3 (1.9)	14.3 (2.0)	14.1 (2.0)	14.3 (1.6)
Thickness [km]*	1.4 (1.1)	1.5 (1.2)	1.5 (1.1)	1.3 (1.0)
Cloud Optical Depth*	0.25 (0.46)	0.30 (0.52)	0.26 (0.47)	0.20 (0.40)
Max Backscatter Altitude [km]	13.6 (2.0)	13.7 (2.3)	13.5 (2.2)	13.6 (1.8)
Lidar Ratio [sr]*	23.3 (8.0)	22.6 (8.1)	22.8 (7.9)	22.4 (7.9)
Relative freq. opaque cirrus [%]*	20.5	25.2	21.0	17.4
Relative freq. thin cirrus [%]	37.8	37.0	43.2	36.5
Relative freq. SVC [%]*	41.6	37.8	35.8	46.0
Base above the tropopause [%]*	5.9	6.9	5.5	5.3
Top above the tropopause [%]*	15.7	18.7	16.1	12.9
<i>Opaque Layers</i>				
Num. of opaque layers	3251	1283	574	1394
Base Altitude [km]*	10.7 (1.5)	10.6 (1.6)	10.4 (1.5)	10.8 (1.2)
Top Altitude [km]	13.4 (1.6)	13.5 (1.7)	13.1 (1.6)	13.6 (1.4)
Thickness [km]*	2.76 (1.02)	2.84 (1.07)	2.65 (1.04)	2.73 (0.94)
Cloud Optical Depth*	0.93 (0.64)	1.00 (0.66)	0.90 (0.66)	0.86 (0.59)
Max Backscatter Altitude [km]	12.0 (1.7)	12.1 (1.9)	11.6 (1.7)	12.1 (1.5)
Lidar Ratio [sr]*	25.7 (6.3)	26.0 (6.7)	25.8 (6.6)	25.3 (5.7)
<i>Thin Layers</i>				
Num. of thin layers	5985	1888	1183	2914
Base Altitude [km]*	12.9 (1.7)	13.1 (1.9)	12.9 (1.8)	12.8 (1.4)
Top Altitude [km]*	14.4 (1.7)	14.6 (2.0)	14.4 (1.8)	14.3 (1.4)
Thickness [km]*	1.46 (0.78)	1.42 (0.82)	1.49 (0.78)	1.47 (0.74)
Cloud Optical Depth	0.12 (0.07)	0.12 (0.07)	0.12 (0.07)	0.11 (0.07)
Max Backscatter Altitude [km]*	13.7 (1.7)	13.9 (1.9)	13.7 (1.9)	13.5 (1.5)
Lidar Ratio [sr]*	22.8 (7.9)	21.8 (7.7)	21.6 (7.4)	24.3 (8.1)
<i>SVC Layers</i>				
Num. of SVC layers	6581	1924	980	3677
Base Altitude [km]*	14.4 (1.9)	14.7 (2.1)	14.4 (2.1)	14.2 (1.6)
Top Altitude [km]*	14.9 (1.9)	15.2 (2.1)	15.0 (2.1)	14.7 (1.6)
Thickness [km]	0.51 (0.37)	0.50 (0.38)	0.53 (0.38)	0.51 (0.36)
Cloud Optical Depth	0.011 (0.008)	0.011 (0.008)	0.012 (0.009)	0.011 (0.008)
Max Backscatter Altitude [km]*	14.6 (1.9)	14.9 (2.1)	14.7 (2.1)	14.4 (1.6)
Lidar Ratio [sr]*	21.6 (8.4)	19.9 (7.6)	21.5 (8.1)	23.5 (9.0)

Figures:

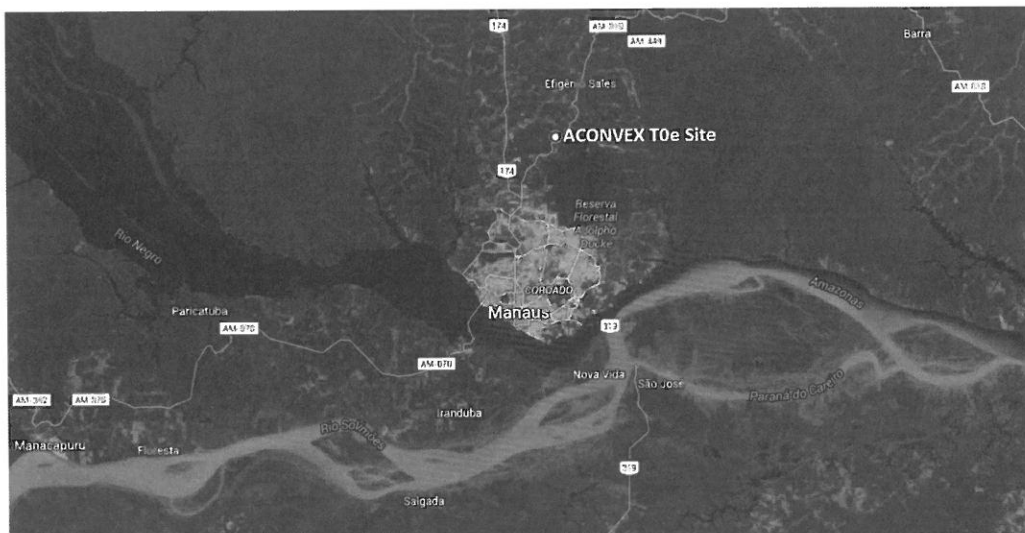


Figure 1. Satellite-based map (Google Earth) showing the location of the lidar site (ACONVEX T0e, 2.89°S 59.97°W), 30 km upwind (north) from downtown Manaus-AM, Brazil.



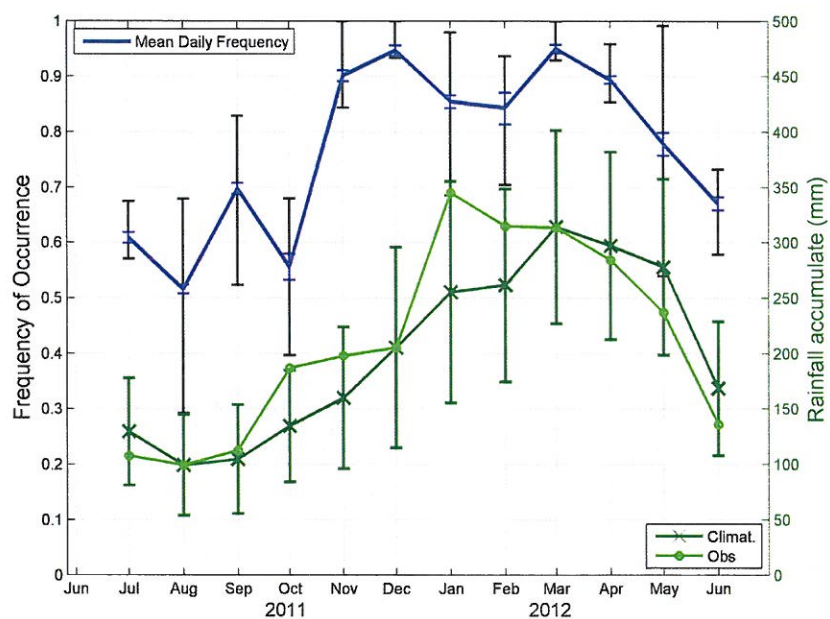


Figure 2. Monthly frequency of occurrence of cirrus clouds from July 2011 to June 2012 (blue line) with the associated statistical error (black). Accumulated (light green) and climatological (dark green) rainfall, shown on the right axis, were obtained from the TRMM 3B42 version 7 dataset averaged over an area of  $10^{\circ} \times 10^{\circ}$ .

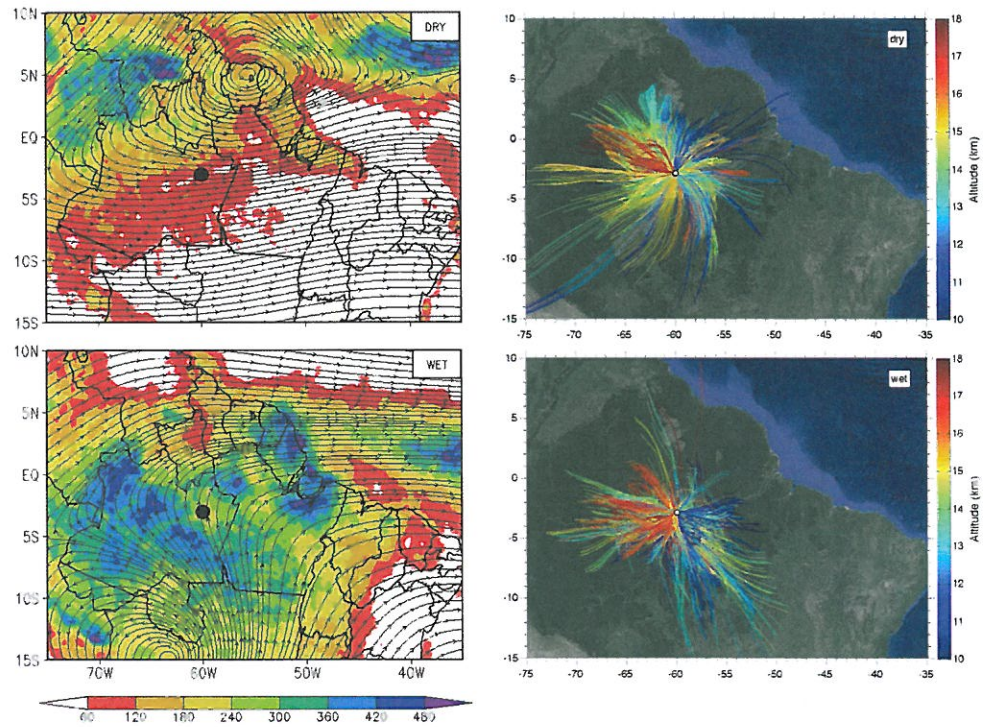


Figure 3. Left panels show mean precipitation (colors, mm month<sup>-1</sup>) from the TRMM 3B42 version 7 and mean wind field (vectors, m/s) at 150 hPa (~14.3 km) from ECMWF ERA Interim reanalysis. Right panels show 24 h back trajectories of air masses arriving at the site at the time and altitude that cirrus layers were detected. Results are shown separately for the dry (JJAS, top) and wet months (JFMA, bottom). Backward trajectories were computed using HYSPLIT model with 0.5° resolution winds from GDAS/NOAA. The experimental site location is indicated in all panels with a circle.



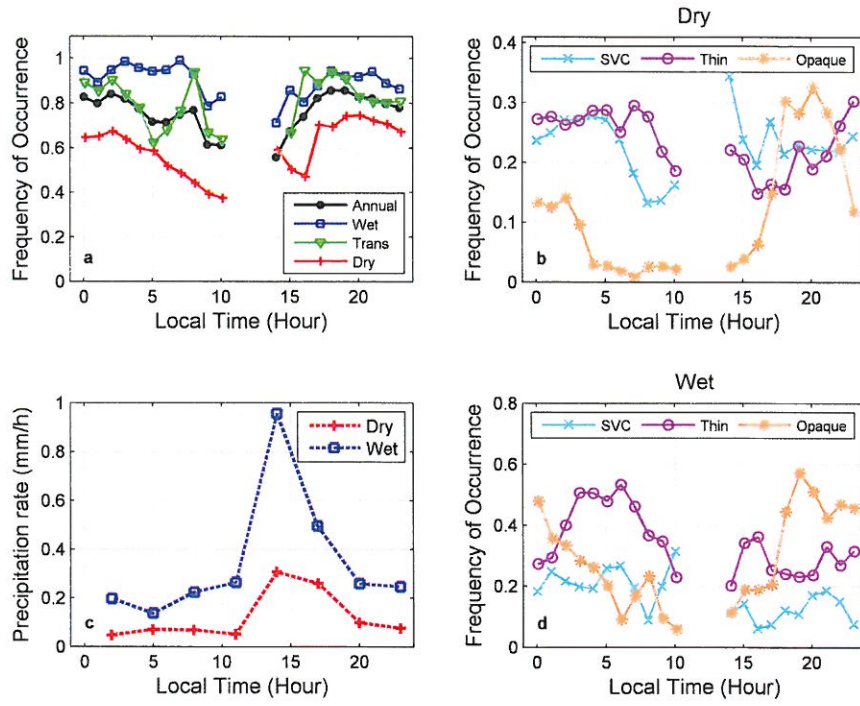


Figure 4. Panel (a) shows the daily cycles of the hourly frequency of occurrence of cirrus clouds for the annual, wet, transition and dry periods. The same is shown for SVC, thin and opaque cirrus clouds during the dry (b) and wet (d) seasons. Mean observed precipitation rate (mm/h) from TRMM version 7 over an area of  $2^\circ \times 2^\circ$  centered on the site, for the dry and wet periods, is given in panel (c).

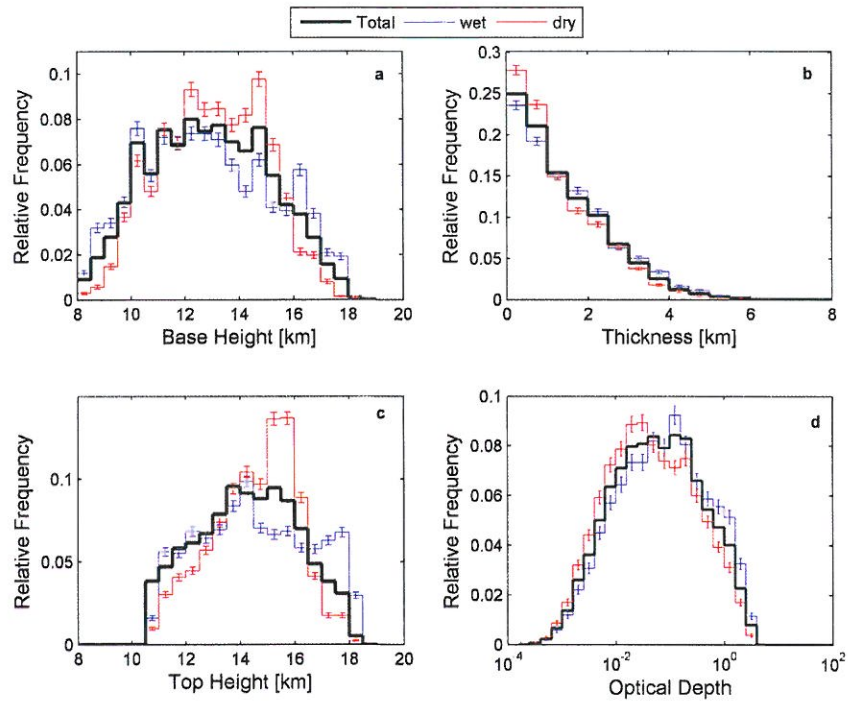


Figure 5. Panels show the normalized histograms of (a) cirrus cloud base, (b) cloud geometrical thickness, (c) cirrus cloud top, and (d) optical depth, for the overall period (black), wet season (JFMA, red) and dry season (JJAS, blue). Error bars indicate the counting statistics uncertainty.

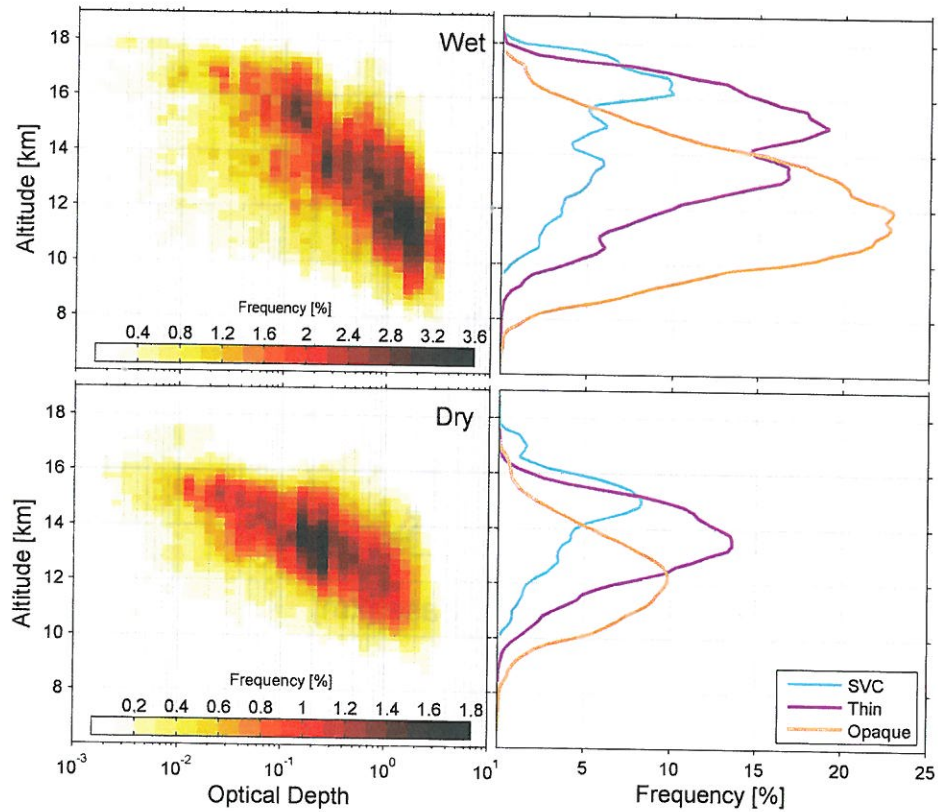


Figure 6. Two-dimensional histograms of cirrus frequency of occurrence with altitude as a function of optical depth during the wet (top) and dry (bottom) season months are shown on the left. The same is shown on the right but integrated for SVC, thin and opaque cirrus clouds optical depths.



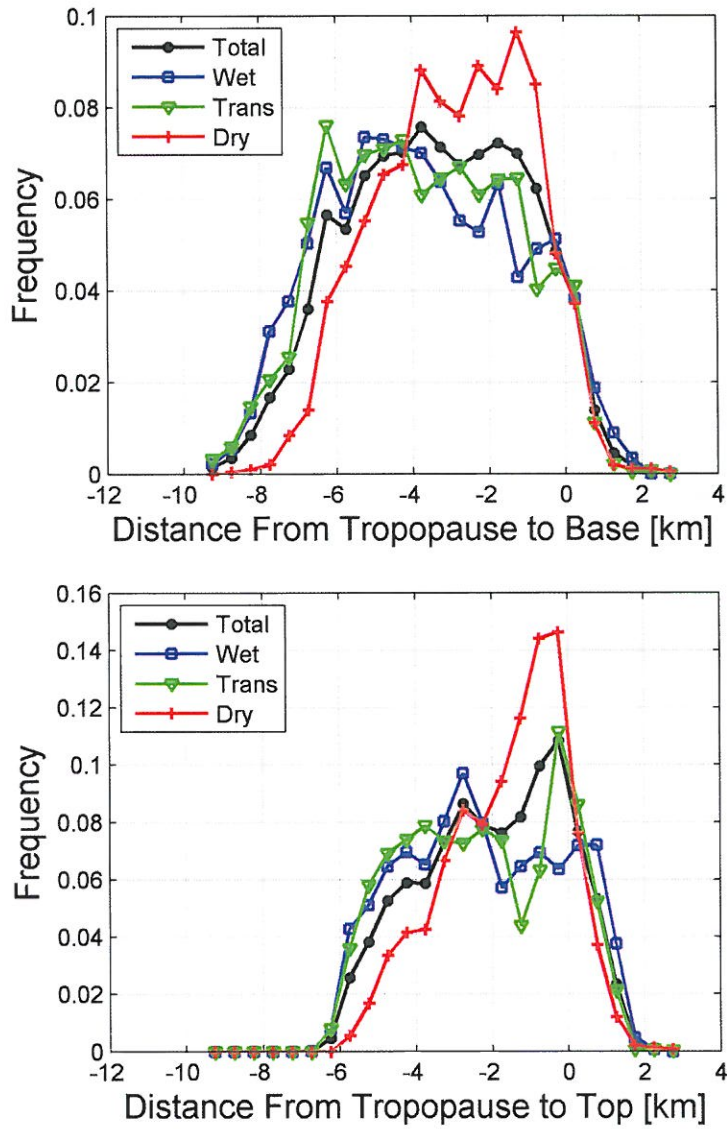


Figure 7. Normalized histograms of the distance of the tropopause to the cirrus base and top are shown for overall period (black) and each season (colors). Negative values mean that clouds are below tropopause. The average tropopause altitude was  $16.2 \pm 0.4$  km.

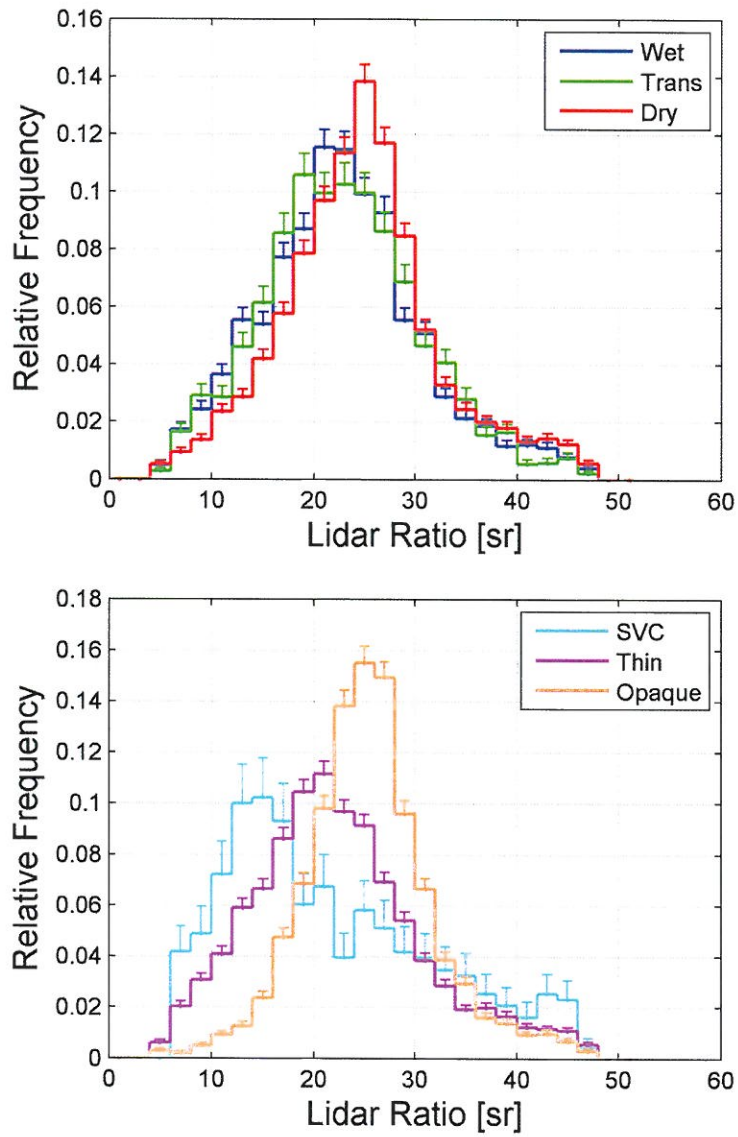


Figure 8. Normalized histograms of the lidar ratio, already corrected for multiple-scattering, for the different seasons (top) and for SVC, thin and opaque cirrus (bottom) are shown. Error bars indicate the counting statistics uncertainty.

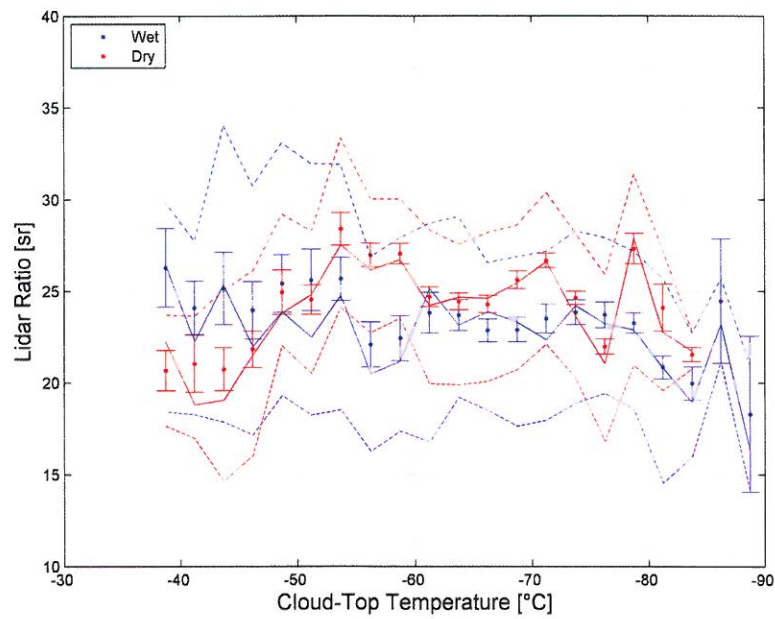


Figure 9. Dependence of the corrected lidar ratio with cloud-top temperature is shown for the wet (blue) and dry (red) seasons. The markers give mean and standard deviation of the mean. The continuous and dashed lines give median and interquartile distance. Temperature is divided in 2.5 °C intervals.