Interactive comment on Variability of cirrus cloud properties using a Polly^{XT} Raman Lidar over high and tropical latitudes" by Kalliopi Artemis Voudouri et al.

Anonymous Referee #1

The paper presents the results of the cirrus cloud observations performed with a ground-based multi-wavelength PollyXT Raman Lidar during sequential periods between 2008 and 2016, in two subtropical stations (i.e. Gual Pahari in India and Elandsfontein in South Africa) and one subartic station (i.e. Kuopio in Finland). An automatic cirrus cloud detection algorithm was developed to derive the cirrus cloud lidar geometrical characteristics (cloud boundaries, geometrical thickness) and optical properties (cloud optical depth, lidar ratio, ice crystal depolarization ratio). Then, a statistical analysis and the seasonal variability of these parameters are presented comparing the results of the three sites at different latitudes. The main results of the study are of interest. However, the authors should better characterize these results explaining the scientific context and their novelty and relevancy, re-organizing the structure of the paper that is not well structured. Some sections and figures lack of an accurate description and need to be completed. A more accurate characterization of the developed algorithm used to derive cirrus geometrical and optical properties is required, adding examples and/or references. The discussion of the results, which, in some parts, does not follow a linear path, should be modified giving more emphasis to the comparison among the different stations. The relationships between aerosol load and cirrus optical properties for the three different sites should be considered and discussed in the paper. Furthermore, an added value of this work could be providing an example on how and which the estimated cirrus parameters could be used in the parameterization schemes of the satellite optical retrievals. These issues need to be addressed to better present and to significantly strengthen the results. Thus, I recommend the publication of the manuscript after major revisions, according with the following observations.

We thank the reviewer for his/her remarks that helped us to improve the manuscript. The reviewer is right that parts of the paper should be restructured, as in the present form is not easy to follow the comparisons of the cirrus properties between the different sites. In the revised version the reviewer's comments have been extensively taken into account, by improving the discussion of many sections (i.e., algorithm description, comparison among the different stations, adding new figures and tables) and by improving the figures that lacked of an accurate description. Below we report the changes included in the revised manuscript as a response to the comments of the reviewer.

Introduction

1) The introduction lacks of a discussion about cirrus retrievals through CALIOP. Please add some discussions and references.

The reviewer is right. The following text has been has been added in the revised version.

In the introduction section at page 2-3, we added the following paragraph:

"There are also satellite based studies from either lidar (CloudAerosol Lidar with Orthogonal Polarization (CALIOP), Dupont et al., 2010) or cloud radar (CloudSat) or combined lidar and cloud radar (e.g. Sassen et al. 2008) retrievals that provide a global view concerning the seasonal frequencies of cirrus clouds and their geometrical and optical properties and their variabilities.

However, there are only few long-term studies based on ground-based lidar systems, while these have a limited geographical distribution. This kind of observations that correspond to different areas and atmospheric conditions are crucial to reveal information of the latitudinal dependence of the cirrus properties and can provide indications about the aerosol effect on the geometrical and optical characteristics of the detected cirrus layers. On top of that, these observations can be further used in the validation and improvement of the satellite retrievals, which provide global distribution of cirrus clouds (Sassen et al., 2008). Given that for satellite retrievals, the main input parameter to the optical processing of the cirrus layers is the lidar ratio, the selected lidar ratio value can introduce errors on the retrieved extinction and optical depth values of the cirrus layers, as it is illustrated by Young et al., (2018). The optical depth comparison of the Version 4.10 (V4) of the CALIOP optical depths and the optical depths reported by MODIS collection 6 show substantial improvements relative to earlier comparisons between CALIOP version 3 and MODIS collection 5, as a result of extensive upgrades of the extinction retrieval algorithm. New apriori information of the lidar ratio value for the cirrus layers, included in Version 4.10 (V4) of the CALIOP data products, led to improvements of the extinction and optical depth estimates of the cirrus cloud layers. Thus, ground based lidar observations of the cirrus properties, that correspond to different areas and atmospheric conditions, are crucial to verify and eventually improve the satellite retrievals.

Reference:

Dupont, J.-C., M. Haeffelin, Y. Morille, V. Noël, P. Keckhut, D. Winker, J. Comstock, P. Chervet, and A. Roblin Macrophysical and optical properties of midlatitude cirrus clouds from four ground-based lidars and collocated CALIOP observations, J. Geophys. Res., 115, D00H24, doi:10.1029/2009JD011943, 2010.

Sassen, K., Z. Wang, and D. Liu, Global distribution of cirrus clouds from CloudSat/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) measurements, J. Geophys. Res., 113, D00A12, doi:10.1029/2008JD009972, 2008.

Young, S. A., Vaughan, M. A., Garnier, A., Tackett, J. L., Lambeth, J. D., and Powell, K. A.: Extinction and optical depth retrievals for CALIPSO's Version 4 data release, Atmos. Meas. Tech., 11, 5701–5727, https://doi.org/10.5194/amt-11-5701-2018, 2018.

2) Lines 61-67, the novelty of the work needs to be discussed and detailed.

The text is modified accordingly and the following sentence is added:

"The aim of this work is to retrieve and analyze the cirrus geometrical, intensive and extensive optical properties at different latitudes (subtropical and subarctic), from observations derived with the same ground based lidar system, which partly fills the gap concerning the latitudinal coverage of existing ground-based lidar studies. Then the observed differences are discussed in order to identify the possible causes. The information of the lidar ratio is an important parameter for the inversion of lidar signals in instruments that do not have Raman channel and space-based lidars, such as CALIPSO, depend on a parameterization that may vary with location. Thus, information provided by well-calibrated ground based measurements is quite critical. Analysis of the lidar ratios values derived from lidar measurements in different parts of the world, where different atmospheric and aerosol conditions prevail, will provide results that are more representative of the actual conditions and thus their use will lead to reductions in the uncertainties of the satellite retrievals."

3) Section 2, Line 89, please add some details about the nature of the aerosols and their seasonality over the three different sites with appropriate references.

The text is modified accordingly and the following paragraph is added:

"The one year aerosol analysis of lidar observations in Gual Pahari (Komppula et al., 2012) showed that in the summer, the measured air masses were slightly more polluted and the particles were a bit larger than in other seasons (higher Angström exponent values), with the main aerosol sources to be the local and regional biomass and fossil fuel burning. The annual averages revealed a distinct seasonal pattern of the aerosol profiles, with aerosol concentrations slightly higher in summer (June – August) compared to other seasons, and particles larger in size. During the summer and autumn, the average lidar ratios were larger than 50 sr, suggesting the presence/dominance of absorbing aerosols from biomass burning.

The lidar observations that were performed at Elandsfontein and used for aerosol characterization for the corresponding study period (Giannakaki et al. 2016) showed that the observed layers were classified as urban/industrial, biomass burning, and mixed aerosols using the information of backward trajectories, MODIS hotspot fire products and in situ aerosol observations. The analysis of the seasonal pattern of vertical profiles of the aerosol optical properties showed that the more absorbing (higher Lidar ratio at 355 nm) biomass particles showed a maximum on August and October, while the category of Urban/industrial had their peak on January, March and May.

Kuopio is an urban area and constitutes a low-aerosol-content environment. The columnar analysis of sunphotometer observations (Aaltonen et al., 2010) revealed that the high Angstrom exponent values observed can be possible linked with the presence of fine particles, while the seasonal analysis of the optical depth showed that there is no significant variation."

<u>References</u>:

Aaltonen, Veijo & Rodriguez, Edith & Kazadzis, Stelios & Sogacheva, Larisa & Arola, Antti & de Leeuw, Gerrit.: Characteristics of the aerosol climatology over Finland based on the optical columnar properties. 12. 10788, 2010.

Giannakaki, E., van Zyl, P. G., Müller, D., Balis, D., and Komppula, M.: Optical and microphysical characterization of aerosol layers over South Africa by means of multi-wavelength depolarization and Raman lidar measurements, Atmos. Chem. Phys., 16, 8109–8123, https://doi.org/10.5194/acp-16-8109-2016, 2016.

Komppula, M., Mielonen, T., Arola, A., Korhonen, K., Lihavainen, H., Hyvärinen, A.-P., Baars, H., Engelmann, R., Althausen, D., Ansmann, A., Müller, D., Panwar, T. S., Hooda, R. K., Sharma, V. P., Kerminen, V.-M., Lehtinen, K. E. J., and Viisanen, Y.: Technical Note: One year of Raman-lidar measurements in Gual Pahari EUCAARI site close to New Delhi in India – Seasonal characteristics of the aerosol vertical structure, Atmos. Chem. Phys., 12, 4513-4524, https://doi.org/10.5194/acp-12-4513-2012, 2012.

<u>Section 3 and Section 4</u>

4) As the retrieval of optical properties is part of the retrieval algorithm, I would suggest merging Section 3 and Section 4 in three different subsections (3.1, 3.2 and 3.3). The contribution of the background aerosol load to the computation of cirrus cloud products is not negligible. This aspect should be discussed with the appropriate references not only in the last part of the Conclusions but also in this section. Please discuss this point.

Section 3 and 4 have been merged accordingly. See also comment 3 for the discussion of the background aerosol load. In principal, we assume aerosol free (molecular) region in the altitudes above 6km where our algorithm is applied. This is a reasonable assumption. Climatological studies for these areas, show for Elandsfontein that the upper aerosol layers were found ~3.5km (Giannakaki et al., 2016), while for Gual Pahari the upper layers were below 6km (Komppula et al., 2012) for the period reported in the manuscript.

5) Lines 100-102, please discuss the normalization of signal (step b). How this normalization enhances the method applicability in different atmospheric conditions?

The normalization is applied to ensure the applicability of the method (use of threshold criteria for cirrus boundaries) to all the lidar systems. Given that lidar signals are uncalibrated and signal levels from one lidar system to another can be rather different, the normalization ensures the applicability of the criteria used by Baars et al., 2008. We normalized the range-corrected signal by its maximum value found below 1500 m. (below 2500 for Elandsfontein), which is usually the maximum value of the range corrected signal within the Boundary Layer, as proposed by Baars (2008), in order to use the same threshold values for the cirrus boundaries.

Baars, H., Ansmann, A., Engelmann, R., and Althausen, D.: Continuous monitoring of the boundary-layer top with lidar, Atmos. Chem. Phys., 8, 7281–7296, https://doi.org/10.5194/acp-8-7281-2008, 2008.

6) Lines 113-115, it is not clear to me if the estimated cirrus geometrical and optical parameters are referred to 60-min averages. If yes, it means that, for example, for the cirrus of Fig.2 the detection algorithm will retrieve one cirrus parameter per hour. Is it correct? Please clarify this aspect.

The reviewer is right. The estimated cirrus geometrical and optical parameters are referred to 60-min averages, so the Figure 3 has changed in the revised version of the manuscript, presenting the hourly means profiles.

7) Lines 116- 119, please add more details and references about the criteria a) and c).

The reviewer is right. We also applied an additional one, a threshold temperature to the cirrus top in order to assure that at cloud top no liquid water is present any more and we also changed the one in the cirrus base, so as to enhance the assumption that no liquid is present, as ice formation occurs predominantly via the liquid phase at T<-27°C (Westbrook et al., 2011).
The sentence has been changed to the following:

"Finally, cloud retrievals from the algorithm are classified as cirrus clouds when the following four criteria were met: i) the particle linear depolarization value is higher than 0.25 (Chen at al., 2002; Noel et al., 2002), ii) the altitude is higher than 6km and iii) the base temperature is below -27°C (Goldfarb et al., 2001; Westbrook et al., 2011) and iv) the top temperature is below -37°C (Campbell et al., 2015)."

<u>References:</u>

Campbell, J. R., Vaughan, M. A., Oo, M., Holz, R. E., Lewis, J. R., and Welton, E. J.: Distinguishing cirrus cloud presence in autonomous lidar measurements, Atmos. Meas. Tech., 8, 435– 449, doi:10.5194/amt-8-435-2015, 2015.

Chen, Wei-Nai & Chiang, Chih-Wei & Nee, Jan.: Lidar Ratio and Depolarization Ratio for Cirrus Clouds. Applied optics. 41. 6470-6. 10.1364/AO.41.006470, 2002.

Goldfarb, L., Keckhut, P., Chanin, M.-L., and Hauchecorne, A.: Cirrus climatological results from lidar measurements at OHP (44°N, 6°E), Geophys. Res. Lett., 28, 1687–1690, 2001.

Noel, Vincent & Chepfer, Helene & Ledanois, Guy & Delaval, Arnaud & Flamant, Pierre.: Classification of Particle Effective Shape Ratios in Cirrus Clouds Based on the Lidar Depolarization Ratio. Applied optics. 41. 4245-57. 10.1364/AO.41.004245, 2002.

Westbrook, C. D., and Illingworth, A. J. (2011), Evidence that ice forms primarily in supercooled liquid clouds at temperatures > −27°C, Geophys. Res. Lett., 38, L14808, doi:10.1029/2011GL048021.

8) Lines 143-144, the depolarization condition (particle linear depolarization > 0.25) is used only for Kuopio or also for the other sites? Which is the magnitude of the error/bias introduced by the Rayleigh calibration method? Despite the different calibration method, it could be of interest to show the depolarization ratio values of the other two sites.

Rayleigh calibration could produce large errors on the particle linear depolarization, so we choose to show the climatology of the values only for Kuopio. In the Rayleigh calibration method a very low amount of strong depolarizing aerosols, like dust or ice crystals in the assumed calibration range, causes large errors of the calibration factor and consequently in the particle linear depolarization, as described in detail in Freudenthaler et al. (2009). The error introduced by the Rayleigh calibration, is associated to the reference region assumed, which should be carefully chosen, and can be of the order of 10-40%. Therefore we only used these depolarization ratios only as proxies for the presence of cirrus clouds and we did no show any climatological values, which could be misleading, when compared to the ones accurate calibrated.

Freudenthaler, V., Esselborn, M., Wiegner, M., Heese, B., Tesche, M., Ansmann, A., Müller, D., Althausen, D., Wirth, M., Fix, A., Ehret, G., Knippertz, P., Toledano, C., Gasteiger, J., Garhammer, M., and Seefeldner, M.: Depolarization ratio profiling at several wavelengths in pure Saharan dust during SAMUM 2006, Tellus B, 61, 165–179, doi:10.1111/j.1600- 0889.2008.00396.x, 2009.

9)Line 156, it might be helpful to clarify the use of the Eloranta model writing the equation of the term P1(z) of the equation (4) and discussing the assumptions.

The reviewer is right. The equation has changed in the revised version of the manuscript. The model inputs are:
(i) the laser beam divergence
(ii) the receiver field of view
(iii) the cirrus effective radius We use the values given by Wang and Sassen (2002), who had related the effective radius with cirrus cloud temperature.

(iv) the measured single scattering extinction profile (or the lidar ratio multiplied by the backscatter for the daytime measurements).
(v) the order of scattering

To calculate the multiple scattering correction, the code applies an iterative method including the following steps:
i) The measured extinction profile of the cirrus layer is provided.
ii) With the provided effective radius profile of the cirrus layer (linear relation of the effective radius with the cirrus temperature derived from radio soundings) and the effective (measured) extinction coefficient α par (z), the model provides the ratio P (z)/P (1) (z).
iii) From (2) a first value for the correcting factor F(z) can be worked out.
iv) The iterative procedure continues till the calculation of a stable correcting factor F(z) is found.
v) The corrected extinction can be then calculated from equation (5) in the manuscript and hence the value of lidar ratio.

The following sentence has been added in the manuscript: "The model assumes cirrus made up of hexagonal ice crystals and the model inputs are: (i) the laser beam divergence, (ii) the receiver field of view, (iii) the cirrus effective radius, (iv) the measured single scattering extinction profile (or the lidar ratio multiplied by the backscatter for the daytime measurements) and (v) the order of scattering. The estimation of the cirrus effective radius was taken from Wang and Sassen (2002), based on the linear relation of the effective radius with the cirrus cloud temperature derived from radio soundings.
For the multiple scattering calculation, the code applies an iterative method including the following steps:
i) The measured extinction profile of the cirrus layer is provided (a1).
ii) With the provided effective radius profile of the cirrus layer (linear relation of the effective radius with the cirrus temperature derived from radio soundings) and the measured extinction coefficient, an iterative procedure provides the ratio P tot (z)/P(z).
iii) From (ii) a first value for the correcting factor F(z) can be worked out.
iv) The iterative procedure continues till the calculation of a stable correcting factor F(z) is found.
v) The corrected extinction can be then calculated from equation (5) in the manuscript and hence the value of lidar ratio."

Section 5
10) *The authors decided to present the results for the estimated geometrical and optical cirrus parameters for each site (sub-sections 5.0.2, 5.0.3 and 5.0.4, respectively). In my opinion, this choice makes the discussion of the results confusing. Another choice, which could help the comparison between subtropical and sub-artic sites, could be to divide the results according to geometrical and optical parameters (two sub-sections). This latter option allows both to improve the description and analysis of Fig. 4, Fig.6 and Fig. 7, where the parameters are depicted for all the stations, and to better compare each site. Table 2 should be completed adding also the value of all the other relevant cirrus parameters (e.g. mean/base/top heights, COD, temperature).*

The reviewer is right. In the revised version of the manuscript the results are presented according to geometrical and optical parameters and Table 2 and Table 3 have been added with values of the other relevant cirrus properties. The discussion of the section is presented accordingly.

11) Line 172, from Fig. 3 the diurnally variations cannot be observed. Please remove 'diurnally' or clarify.

The reviewer is right. The word ‘diurnally’ has been removed in the revised version of the manuscript.

12) Lines 172-176, to analyze if the observed cirrus cover annual pattern is significant, it could be useful to show the number of total measurements per months. Considering your dataset, can you exclude that the observed cirrus cover annual pattern is only an indication of the annual pattern of low clouds/rain? Have you tried to compare this pattern with CALIOP observation over Kuopio region?

Figure shows the pattern of cirrus detection and not the pattern of actual cirrus occurrence. As Polly^{XT} measures continuously (24/7) under favor weather conditions, indeed the pattern presented here is be strongly biased by the presence of low clouds and rain. Thus this pattern is not comparable with the one estimated from satellite retrievals and is quite different (see Figure 3 in Sassen et al, 2008).

13) Lines 176-177, could you explain the agreement between cirrus cover and temperature annual pattern? Are there similar results in literature?

The sentence has been rephrased, as it was quite misleading in the previous version of the manuscript. We did not aim to relate here cirrus cover with the annual pattern of temperature. Our purpose was to relate the low water clouds with temperature values and not the cirrus presence, in order to comment on the absence of cirrus measurements due to low clouds. So, now the sentence has been replaced with the following one:

“This monthly pattern of low clouds existence seems to follow the annual temperature cycle over the region (Jylhä et al., 2004), with maximum temperature values observed during the period April to October, while November to February are the coldest months.”

14) Lines 177-179, please add some numbers about the daytime/nighttime cirrus frequency and the number of total measurements. Could you explain these results?

Table 2 in the revised version of the manuscript, shows the average cloud base and top altitudes and the average geometrical thickness for each site separating daytime and nighttime measurements. The averaged geometrical properties are found to be nearly identical above all sites, with differences less than 0.2km. Table 3 shows the averaged lidar ratio values, which found to be nearly identical above all except Gual Pahari site where average nightttime LR is 4sr higher than that of daytime.
“Table 2 summarizes the mean geometrical values calculated for each site. Differences between the mean values of the geometrical properties in the daytime and nighttime measurements are less than 200m for all sites.“
“Table 3 summarizes the mean optical values discussed above, for the three sites, separating daytime and nighttime observations. Generally, the averaged optical properties values are found to be nearly identical, except one site (New Delhi), where average nighttime optical properties found higher than that of daytime. But since this dataset is limited, it cannot be used as a reference one.”

15) Lines 199-201, is this information relevant?

The reviewer is right. The sentence has been removed in the revised version of the manuscript.

16) Line 204, the AOD is referred to the column below the cirrus? Please explain. It could be of interest to relate AOD to cirrus parameters. Could you deepen this aspect?

We apologize, this was a typo (AOD instead of COD). The correlation between AOD and cirrus properties would be a wholly different study. However, we proceed in the calculation of the AOD in the free troposphere, in order to have an indication about the calculated COD and the AOD below cirrus (check the answer to question 23).

17) Lines 204-206 and 229-231, the discussion about Fig.5 is limited to these lines and does not give any relevant element of interest. Furthermore, concerning COD distribution, Sassen and Cho classification provides similar information. Please add some more elements of discussion or remove Fig. 5.

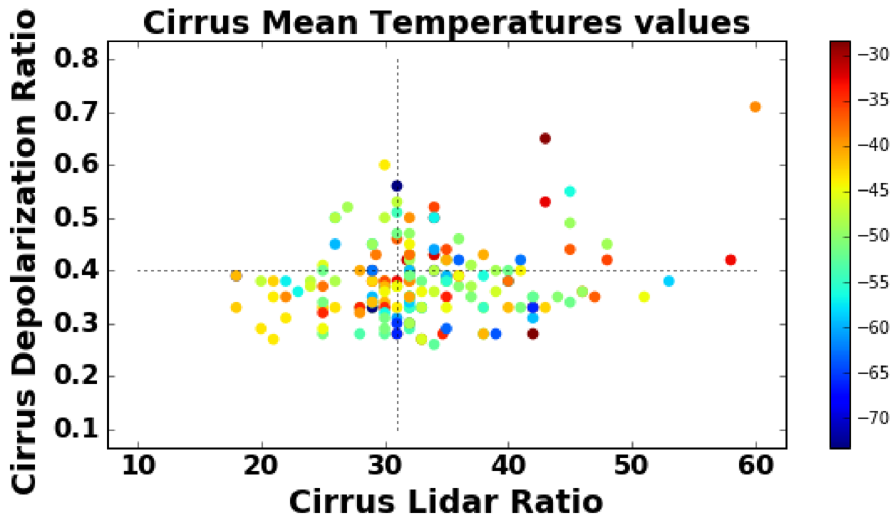
We choose to keep the Figure 7 only with LR values plotted on and to comment accordingly in the results section. The figure is an evidence that although the lidar dataset is not continuous (due to unfavorable weather conditions during winter months), the frequency distributions are representative and even with this scarce sample of data, we observe consistent results with other literature studies.

So, we add a paragraph in the revised version of the manuscript:

"To further investigate the distribution of the cirrus lidar ratio values, we present a histogram of the values observed over Kuopio in Fig. 7. The most frequent measured lidar ratio values range between 28 and 36 sr for 355 nm and 20 and 36 sr for 532 nm. Similar results have been retrieved regarding the variability of LR 532, which is constant from one month to another, as shown. This figure can provide an evidence that although the lidar dataset are not continuous (due to unfavorable weather conditions duting winter months), the frequency distributions are close to normal and thus the statistics shown here have a significance. In addition we can claim that with this scarce sample of data we observe consistent results with a number of other literature studies."

18) Lines 216-229, the plot (e) of Fig. 6 is not discussed in the text. Please add some comments. The particle depolarization ratio together with LR and T could help to understand the cirrus crystal composition, size and shape. Did you find some relationship between delta and LR? Please add some comments and, if relevant, some results.

Indeed, the lidar ratio and the depolarization ratio are related to the microphysics and ice compositions of the cirrus clouds and to our knowledge no clear relationship is reported in literature. Concerning our retrievals, the following Figure (Figure 9 in the revised version of the manuscript) shows the relationship between the optical depth and the lidar ratio:



It can be seen from the above, that the highest values of Cirrus lidar ratio (>40) correspond to higher values of cirrus depolarization ratio (>0.4) and warmer cirrus. Moreover, it can be seen the variety of depolarization ratio values that correspond to the mean value of lidar ratio (~31). A similar behavior is reported in Chen et al. (2002) for lidar ratio values higher than 30 sr. In his study, the relationship between the depolarization ratio and the lidar ratios shows the former split into two groups for lidar ratios higher than 30. One group has high depolarization ratios about 0.5 and another group has 0.2.

The following sentence has been added in the revised version of the manuscript:
"The dependency of the mid temperature with the lidar ratio values at 355nm and the particle depolarization values is further examined. Figure 12 shows that the highest values of cirrus lidar ratio (>40) correspond to higher values of cirrus depolarization (>0.4) and warmer cirrus. Moreover, it can be seen the variety of depol values that correspond to the mean value of Lidar Ratio (∼31). A similar behavior is reported in Chen et al. (2002) for lidar ratio values higher than 30 sr. In his study, the relationship between the depolarization ratio and the lidar ratios shows the former split into two groups for lidar ratios higher than 30. One group has high depolarization ratios about 0.5 and another group has 0.2."

W. Chen, C. Chiang, and J. Nee, "Lidar ratio and depolarization ratio for cirrus clouds," Appl. Opt. 41, 6470-6476, 2002.

19) Line 245, see comment of line 204.
This is a typo, but see also comment on 23.

20) Line 262, see comment of line 204.
This is a typo, but see also comment on 23.

21) Lines 265-269, please add in the discussion the results of the paper of Hoareau et al, 2013, about cirrus measurements at La Reunion sub-tropic site.

The following sentence is added in the revised version of the manuscript:

"Our estimated thickness is slightly smaller than the reported mean value of 2km at La Reunion subtropical region (Hoareau et al., 2012). " Also the values of their study have been added in Table 5 and in Figure 9.

Hoareau, C., Keckhut, P., Baray, J.-L., Robert, L., Courcoux, Y., Porteneuve, J., Vömel, H., and Morel, B.: A Raman lidar at La Reunion (20.8° S, 55.5° E) for monitoring water vapour and cirrus distributions in the subtropical upper troposphere: preliminary analyses and description of a future system, Atmos. Meas. Tech., 5, 1333–1348, https://doi.org/10.5194/amt-5-1333-2012, 2012.

22) Lines 300-323, this sub-section is of interest and it should be extended. In particular, on the basis of your analyses, is it possible to identify the parameters and the threshold values that could be used in satellite parameterization schemes? How the latitude dependence affect the variability of these parameters?

As latitudinal dependence is found, different parameterization would be necessary to future satellite retrievals. The parameters to be taken into account should be:

i) the LR value selected for the different counterparts. A latitudinal variation can be seen in the lidar ratios with the lowest values found over the tropical region and over South Africa (Table 2 and Table 3).
ii) LR values seem to be almost constant between day and night retrievals, except for the Gual Pahari site, where the dataset is not extensive and could not be used as a reference one.

Also Table 3 has been added, summarizing most of the cirrus clouds geometrical and optical properties of ground-based lidar observations reported in literature. Overall, we can conclude that cirrus cloud thicknesses are greatest in the tropics and decrease toward the poles and concerning the lidar ratio values, these seem to be an increasing trend towards the north pole.

The following sentence is added in the revised version of the manuscript:

"The reported values in literature from previous studies based on lidar ground-based datasets and the current one, are listed in Table 4. Generally, cirrus layers have been observed up to altitudes of 13km above Gual Pahari, whereas they have only been detected to about 1km lower at the other two regions and this conclusion is in accordance with the Cloudsat observations (Sassen et al., 2008). Based on the satellite information, the derived cirrus cloud thicknesses was found to be larger in the tropics and decreasing toward the poles. Also from the values reported from groundbased studies, a pattern can be concluded: cirrus cloud geometrical properties peaks around the equator and at midlatitudes sites, with generally decreasing amounts as the poles are approached. On the other hand, the lidar ratio values seem to follow a diverse relation, showing greater values moving to the poles. In our study, larger values of LR is found for the subarctic station and smaller LR were observed for Gual Pahari and Elandsfontein."

23) Line 307, as already mentioned, the relationships between aerosol load and cirrus optical properties should be discussed more in details with a dedicated sub-section. In particular, the aerosol extinction below the cirrus *and the type of aerosol could be of interest to understand the role of aerosol in cirrus formation. Do you have any analysis related to this?*

Measurement Site	Kuopio	Elandsfontein	Gual Pahari
Type of aerosols	Fine particles	biomass burning aerosols and mixtures of biomass burning aerosols with desert dust particles and urban/industrial particles	dust particles, biomass burning
AOD FT	0.01 ± 0.01	0.06 ± 0.04	0.09 ± 0.03
COD	0.25 ± 0.27	0.35 ± 0.30	0.60 ± 0.40

Giannakaki et al. (2016) showed that the aerosol classification over South Africa indicates mostly biomass burning aerosols and mixtures of biomass burning aerosols with desert dust particles, as well as the possible continuous influence of urban/industrial aerosol load in the region.
New Delhi, represents a semi-urban environment surrounded mainly by agricul tural test fields and light vegetation. The seasonal characteristics of the aerosol vertical structure performed there (Komppula et al., 2012) indicate the presence of dust particles due to the Asian dust storms.
Kuopio is a semiurban site, where mostly fine particles exist (Aaltonen et al., 2012).

References

Aaltonen, Veijo & Rodriguez, Edith & Kazadzis, Stelios & Arola, Antti & Amiridis, Vassilis & Lihavainen, Heikki & de Leeuw, Gerrit: On the variation of aerosol properties over Finland based on the optical columnar measurements. Atmospheric Research. 116. -. 10.1016/j.atmosres.2011.07.014, 2012.

Giannakaki, E., van Zyl, P. G., Müller, D., Balis, D., and Komppula, M.: Optical and microphysical characterization of aerosol layers over South Africa by means of multi-wavelength depolarization and Raman lidar measurements, Atmos. Chem. Phys., 16, 8109–8123, https://doi.org/10.5194/acp-16-8109-2016, 2016.

Komppula, M., Mielonen, T., Arola, A., Korhonen, K., Lihavainen, H., Hyvärinen, A.-P., Baars, H., Engelmann, R., Althausen, D., Ansmann, A., Müller, D., Panwar, T. S., Hooda, R. K., Sharma, V. P., Kerminen, V.-M., Lehtinen, K. E. J., and Viisanen, Y.: Technical Note: One year of Raman-lidar measurements in Gual Pahari EUCAARI site close to New Delhi in India – Seasonal characteristics of the aerosol vertical structure, Atmos. Chem. Phys., 12, 4513-4524, https://doi.org/10.5194/acp-12-4513-2012, 2012.

24) Line 310, could you explain the choice of using the cirrus base temperature instead of the mean/top temperature as independent parameter?

The reviewer is right that the cirrus base temperature doesn't provide more information and the mean temperature can be more representative of the dependence of geometrical and optical properties. In the revised version of the manuscript, all figures have been updated with the mid temperature values.

25) Lines 315 and 319, please replace 'Fig.10' with 'Fig. 8'.

As some figures added in the revised version of the manuscript, the order has been changed and the Figure numbers have been corrected.

26) Line 321, from Fig.8d the particle depolarization increases is not clear. Is it significant?

Indeed it is not significant. The sentence has been rephrased in the revised manuscript, as follows: “No clear tendency is found, as the variability of this parameter is relatively constant, with a slightly increase of the particle depolarization with the increasing mid temperature”.

Conclusions

27) To summarize the results of this work, it would be useful to add a resuming table that, according to the different latitudes, compares the retrieved cirrus parameters to the main results of the literature reported in the paper.

We thank the reviewer for this comment. Table 5 is added in the revised version of the manuscript, including all the information of the cirrus properties based on ground-based lidar observations reported in the literature for the different latitudes. A latitudinal dependence of the cirrus cloud can be seen. See also answer to question number 22.

The following sentence is added in the revised version of the manuscript:

“The three presented datasets are derived from different latitudinal and climatic sites. In this section we firstly examine the latitudinal dependence of the cirrus geometrical and optical properties. The reported values in literature from previous studies based on lidar grounbased dataset and the retrievals of the current one are listed in Table 5 and plotted in Figure 9 for comparison. We can note, that the cirrus geometrical properties and the lidar ratio values may vary greatly depending on the latitude and an decreasing trend of the geometrical boundaries with the rise of the distance from the equator is obvious, also reported by satellite observations (Sassen et al., 2008). Generally, cirrus layers have been observed up to altitudes of 13km above Gual Pahari, whereas they have only been detected to about 1km lower at the subarctic region and this conclusion is in accordance with the Cloudsat observations (Sassen et al., 2008). Based on the satellite information, the derived cirrus cloud thicknesses was found to be larger in the tropics and decreasing toward the poles. Also from the values reported from groundbased studies, a pattern can be concluded: cirrus cloud geometrical properties peaks around the equator and at midlatitudes sites, with generally decreasing amounts as the poles are approached. On the other hand, the optical properties seem to follow a diverse relation, showing greater values moving to the poles. In our study, larger values of COD 355 and smaller LR were observed for Gual Pahari and Elandsfontein. The larger variability of the optical properties at the two subtropical regions, relative to Kuopio, could be related to the larger and variable aerosol load over these regions.”