Dear reviewer,

I attach in this document the answers to your comments. But first of all, I would like to thank you for spending time with the review of this manuscript. The answers are in blue and the references made to the lines are made with respect to the new version of the manuscript.

Line 27:

The introduction is a little misleading beginning with Aerosol-radiation as well as aerosol-cloud interactions, despite neither being the subject of this paper. I suggest that the first paragraph be adjusted to begin by discussing the importance of cirrus as is done halfway through the paragraph.

I accept your suggestion and now the paragraph starts directly with the topic of cirrus clouds. I copy the beginning of the paragraph.

"The radiative effect of high-altitude cirrus clouds plays a fundamental role in the global radiation budget (Liou, 1986; Lolli et al., 2017). Despite that, they have been designated as poorly understood by (IPCC, 2021) because of a lack of knowledge of their dynamic, microphysical and radiative properties. Indeed, cirrus cloud critical role in the climate comes from the fact … "

Line 41:

I suggest the second paragraph omit the first two sentences and begin with "Cirrus clouds can form by different …"

The definition of Met Office was showed because we wanted to emphasize the composition of cirrus clouds. However, I accept your suggestion and now the Met Office definition has been removed. I copy the beginning of the paragraph.

"Cirrus clouds are mainly composed ice crystals and can form through different atmospheric mechanisms, giving rise to cirrus clouds with different physical, geometrical and optical properties."

Line 53:

I suggest that the third paragraph could be made stronger by being arranged in an argument that motivates this work as follows:

1. Ice cloud microphysics and their relationship to optical/radiative properties is complex. 2. Remote sensing of cirrus properties requires the assumption of a crystal habit or adoption of a particular empirical model, which complicates the results.

3. Lidar provide the ability to infer cloud optical depth etc. without making such assumptions.

This provides the same background but also more clearly motivates the importance and use of lidar remote sensing.

I accept your suggestion and after the explanation of the different ways of calculating the radiative properties of cirrus clouds, the focus has been changed to provide more motivation. I copy the paragraph.

"Ice cloud microphysics and their relationship to optical/radiative properties is complex. Cirrus clouds can be characterized by some key parameters such as the mid-cloud altitude and temperature, cloud extinction coefficient, cloud optical depth, lidar ratio (LR) or linear cloud depolarization ratio (LCDR). While the LR and LCDR are related with the microphysical properties of the ice crystals contained in cirrus clouds, such as their shape and/or orientation, the mid-cloud altitude and temperature as well as the cloud extinction coefficient play an important role in determining the cloud radiative properties. Up to the present date, there is no exact theoretical solution for scattering and absorption by non-spherical ice particles (Liou and Takano, 1994). Nevertheless, scattering models for cirrus clouds have been developed, such as (Baran et al, 2009, 2011a, b) which relates the cirrus ice water content and mid-cloud temperature with its extinction coefficient and radiative properties. Alternatively, (Heymsfield et al., 2014; Dolinar et al., 2022) propose a relationship between the ice water content with the extinction coefficient and the cloud temperature with the effective geometric diameter of ice crystals. From these properties, the cirrus cloud radiative properties can be calculated with the (Fu et al., 1998, 1999) parametrizations. These and other ways of obtaining the radiative properties of cirrus clouds have several points in common, such as the need to calculate the cloud extinction, where the application of remote sensing is essential, or the assumption of the ice crystal shape distribution in empirical models, further complicating the results."

Line 68:

Lidar systems do not measure vertical profiles of extinction, in general, but in some cases can retrieve it.

Right, lidar systems do not measure directly vertical profiles of extinction, but they can retrieve them. Therefore, the verb measure has been changed to retrieve.

Line 113:

Multiple scattering contributions do not depend only on the receiver field of view. The other relevant factors should be mentioned and additional references should be provided to justify this choice (e.g. Shcherbakov et al. 2022).

Right, a more rigorous explanation has been made in line 206. I copy the explanation.

"The multiple scattering factor, η, is introduced by (Platt, 1973, 1979). The multiple scattering effect depends on laser beam divergence, receiver field of view, the distance between the light source and the scattering volume (Wandinger, 1998; Wandinger et al., 2010; Shcherbakov et al., 2022). In this study the multiple scattering effect is considered negligible for lidar signal measured by the MPL system due to its narrow field of view, the mean distance between cirrus clouds and the MPL, the small cirrus cloud optical depth (generally COD < 0.3) and the magnitude of cirrus cloud extinction (αp < 1 km−1) retrieved (Campbell et al., 2002; Lewis et al., 2016; Shcherbakov et al., 2022)."

Line 234:

This is not the definition of the cloud optical depth. The optical depth is the vertical integral of the volume extinction coefficient. Definitions need to stay consistent to preserve meaning. This equation should be modified to explicitly include the multiple scattering correction, with the note that it is assumed to be negligible.

Right, the notation of the volume extinction coefficient has been changed and in line 203, the volume particle extinction coefficient has been denoted as the volume effective extinction coefficient corrected by multiple scattering errors, whose mathematical expression is $\alpha_p = \eta\, \alpha_{ef}$, being α_{ef} the volume effective extinction coefficient, which is measured by the MPL system.

Equations:

Please use the same notation for integrals over range/altitude. The vertical coordinate variously appears as x, u, and z which is confusing.

Ok, the notation for integrals was unified with the variable z.

Line 278:

This does not seem like a very precise convergence criterion.

The convergence criterion is 1 sr and is very precise. No convergence problems have been found in this respect. In fact, this iterative algorithm with the convergence criterion of 1 sr has an average of 3 iterations.

Line 313:

I am not sure about these criteria. Does this eliminate the possibility of multiple layers of cirrus? Shouldn't we want to know the properties of both layers?

Yes, we have removed the possibility of multi-layers of cirrus clouds, because with these conditions it is not possible to have a molecular region above and below each cirrus, in order to be able to apply the two-way transmittance method.

In the case of a multi-layer cirrus cloud, if the distance between clouds is less than 1 km, it is analyzed as if they were one cloud in total, not as several cirrus clouds in close proximity. On the contrary, it could not be considered that below the upper cirrus in the vertical profile there is a Rayleigh zone. The distance required for normalization in Rayleigh zones is 5 km above the cirrus cloud and 1 km below.

I would like to know the properties of all the cirrus layers but with the two-way transmittance method developed in this manuscript it is not possible.

Line 322:

A success rate of 55% indicates that a significant fraction of data are omitted from the analysis. Any systematic reason for the omission of the data might substantially alter the resulting analysis. For example, it is stated at Line 318 that cases with high lidar ratio, typically with high levels of noise, are discarded. If this noise is caused by low signal strength due to strong attenuation (rather than noise in the lidar signal itself or solar noise), then this indicates a systematic sampling bias that should be discussed. It is not clear whether the cirrus category in Figure 3 only includes the 203 cases, as a COD is derived, or whether the success of the two-way transmittance method is judged based on the lidar ratio. I suggest separating results into "non-cirrus, successful cirrus, failed cirrus" cases. It was stated earlier that the two-way-transmittance test will fail for very optically thin clouds (i.e. subvisible). Some justification is required for why the statistics of subvisible cirrus should be treated as representative. Uncertainties should be propagated to establish the precision of these retrievals.

I will summarize the number of cirrus cases found. In this manuscript, only 1025 days have been analyzed, at 00 and 12 UTC, so there are 2050 cases. Of these 2050 cases, a cloud has been detected with MPLNET products in 1019 cases (49.7%). Of these 1019 cloud cases, at least one cirrus cloud has been detected in 367 cases (36% of sub-dataset of 1019 cloud cases). On the other hand, of these 367 cases, 164 cases could not be correctly applied to the two-way transmittance method. In line 321, the detection of errors in the application of the two-way transmittance method is explained in more detail. I copy the paragraph.

"Of these 367 cases, the two-way transmittance method has only been correctly applied to 203 cases, denoted as "successful" 320 cirrus. Of the 164 cases of cirrus clouds to which the two-way transmittance method could not be correctly applied, denoted as "failed" cirrus, in 29%, the Rayleigh zone above and below the cirrus cloud could not be guaranteed, in 46% a negative COD was calculated and in 25% a LR higher than 100 sr was estimated. Of the "failed" cirrus cases for which the Rayleigh zone above and below the cirrus cloud could be guaranteed, in 92% of the cases, the cirrus had a very small lidar signal peak and in 8% of the cases, although the lidar signal peak associated to the cirrus cloud was noticeable, the signal was excessively noisy."

A deeper analysis of "failed" cirrus clouds has been also developed. In Figure 3a, the temporal distribution of "failed" cirrus clouds was added and Figure 3b has been better explained in its figure caption.

Figure 4:

Again, the daytime/nighttime contrast should be partitioned by retrieval failure or success.

It was added in line 365.

"The efficiency of the two-way transmittance method does not seem to be affected considerably, since the success rates of this method for cirrus clouds during daytime (62%) and nighttime (51%) are similar."

Figure 5a:

The bins are not particularly clear. I suggest logarithmically spaced bins as well.

Right, the figure was changed and for sub-visible and visible cirrus, a logarithmic grid was used. I attach the new figure.

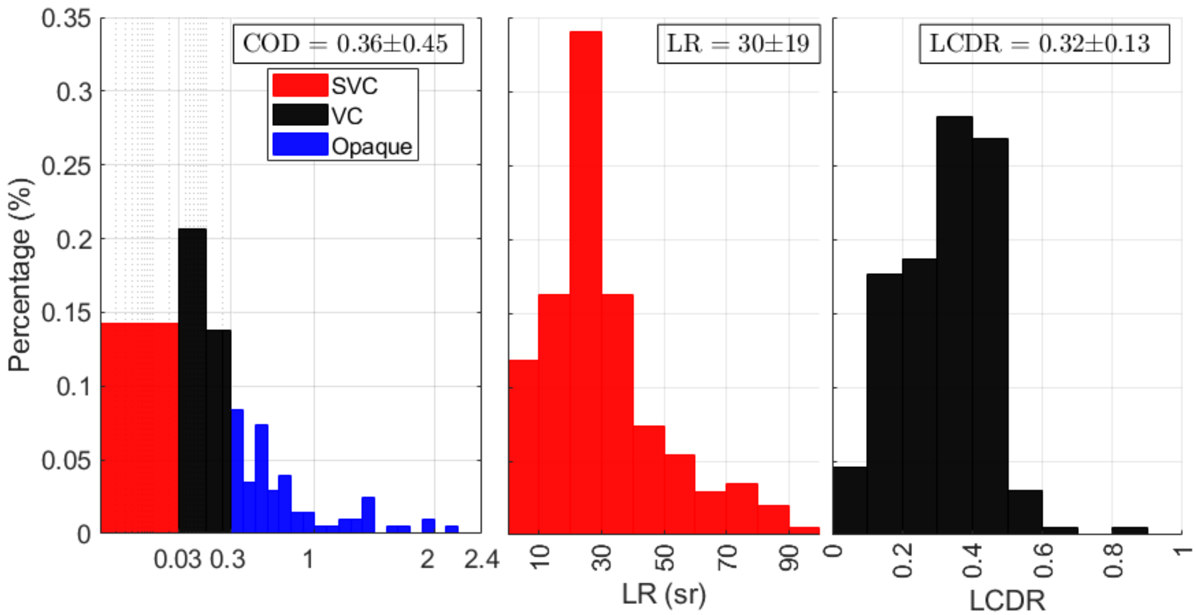

Figure 5. Probability distribution of (left) cloud optical depth, (center) effective column lidar ratio and (right) linear cloud depolarization ratio, calculated using the two-way transmittance method, from 2018 to 2022 in Barcelona. The rectangles in the upper right-hand corners show average values and standard deviations of the distributions. The left figure has a logarithmic grid to show the sub-visible and visible cloud groups.

Table 3:

The meaning of the quantity after the +/- needs to be defined. Is this the standard deviation? Or the standard error in the mean?

Yes, they are mean values and standard deviations. It was changed in line 431.

“**Table 3.** Average and standard deviation values of characteristics of cirrus clouds of ground-based lidar observations, reported in literature. The optical properties have been calculated at 532 nm. Where N is the number of cirrus clouds identified and (%) its percentage with respect to the total number of clouds. The occurrence of SVC, VC and opaque cirrus clouds are made on the number of cirrus N. (a) Tm values have been manually calculated from values of temperature at cloud and top heights, shown in the paper. (b) The geometrical properties show are from an annual average and the optical properties are obtained by the two-way transmittance method applying a multiple scattering correction. (c) The optical properties are calculated at 355 nm.”

Line 430:

I would disagree with the conclusion that the lidar ratio has a generally increasing trend towards the poles. Instead, my conclusion would be “the variability at different sites appears negligible relative to the variability at each site.”

I see a positive trend of the lidar ratio towards the poles, but I agree that there is a large variability at each site. So I have changed the conclusion to the following: “the effective column lidar ratio seems to have a generally increasing trend towards the poles, but no conclusion can be drawn, since the variability at different sites appears negligible relative to the variability at each site.”

Line 452:

It needs to be clarified whether this correlation is between COD and the other cirrus properti es or between log10(COD).

Right, it was changed in line 466.

Figure 6:

The grey shading does not appear to be the 95% confidence intervals of the linear regression. I would expect uncertainty in the slope of the regression to produce diverging bounds on the relationship in a “x” shape, unless the standard error in the slope is negligible compared to the standard error in the intercept, which I would not expect to be the case for the shown data.

Right, only the interception error was considered. It has already been changed. I attach the new figure.

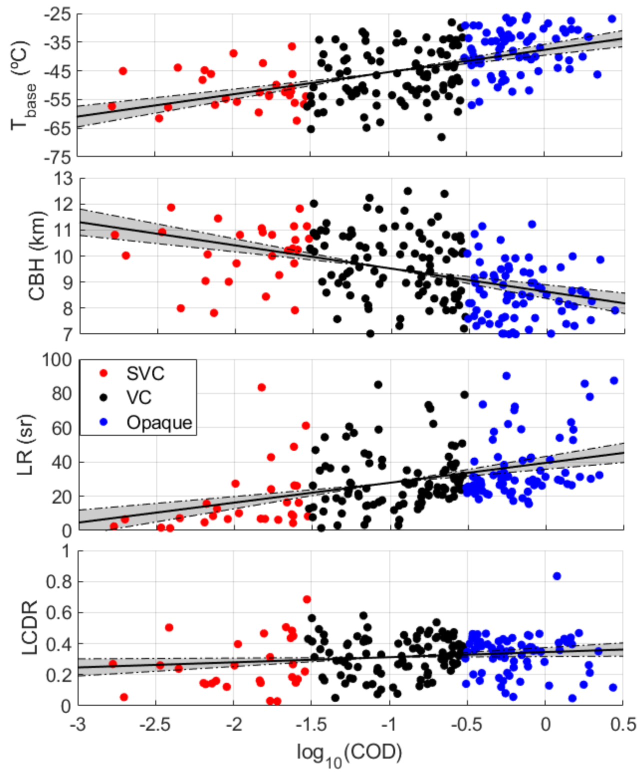

Figure 6. Logarithmic dependence of the cloud optical depth with (a) cloud base temperature, (b) cloud base height, (c) effective column lidar ratio and (d) linear cloud depolarization ratio, for cirrus cases from 2018 to 2022 in Barcelona. The solid black line is the linear regression that has been calculated between the variables and the grey shading with the dash dotted black lines are the 95% confidence limit of the linear regression. The R2 coefficients are (a) 0.26, (b) 0.19, (c) 0.17 and (d) 0.03.

Line 470:

My reading of Figure 6 (bottom) is opposite to the authors in that there is no significant relationship between LCDR and COD. The r-squared value is 0.03. The reference entry for Chen et al. 2002 appears to be incorrect. What I presume to be the correct reference (below) suggests a decreasing relationship between LCDR and COD. This study is distinct in that there is no significant relationship.

Right, I changed the reference of Chen et al., 2002. Sorry for the mistake. The correct reference is "Chen, W.-N., Chiang, C.-W., and Nee, J.-B.: Lidar ratio and depolarization ratio for cirrus clouds, Appl. Opt. 41, 6470-6476, 2002.".

It is true that despite the clear visualization of the positive correlation between LCDR and COD, their r-squared is very low. Therefore, that statement has been changed in the text. (Line 485)

"Likewise, the linear cloud depolarization ratio has a slightly positive tendency with the cloud optical depth, which is negligible because of its low R-squared of 0.03. Moreover, (Chen 485 et al., 2002) found an opposed tendency. Despite that, a positive tendency between LCDR and COD could make sense due to the fact that as the COD increases, the number of ice crystals increases and, as a consequence, the randomly aggregation of ice crystals within the cloud occurs more frequently. As the ice crystals increase in size, they become rougher and consequently, depolarization increases (Yang et al., 2000)."

Figure 7:

The caption refers to a known range of lidar ratio for cirrus clouds being less than 40 sr. Some references are required for this. The authors should bear in mind that in situ measurements of lidar ratio are not column averaged, while what is reported here is an effective column lidar ratio.

The authors should comment on the possibility that the MPLNET cloud classification used to define cloud in this study is misclassifying aerosol as cloud and that that contributes to the low depolarization ratios.

In Figure 7, the lidar ratio interval that was considered as normal for cirrus clouds was 10-40 sr, giving a margin of 10 sr to the range of 20-30 sr which agrees with (Sassen and Comstock, 2001; Yorks et al., 2011; Josset et al., 2012; Garnier et al., 2015; Cordoba-Jabonero et al., 2017). On the other hand, for linear cloud depolarization ratio values, the established range was 0.3-0.5, according to (Sassen, 2005; Giannakaki et al., 2007; Kim et al., 2018; Hu et al., 2021).

I accept the suggestion of the lidar ratio notation and it was changed by effective column lidar ratio. I comment our confidence in MPLNET's products and its procedures on the line 340. The misclassification aerosol as cloud is possible, but I am confident in the reliability of the products, in the absence of evidence to the contrary.

Line 480:

Should the thermodynamics not also be a major indicator here? How many cirrus clouds even have cloud-base temperatures that are above the homogeneous nucleation temperature?

No, because the goal is to analyze the existence of liquid water content on cirrus clouds depending their optical properties. Specifically, we focus on cirrus clouds that have optical properties that do not fit well with the literature. For this reason, the boxes are fixed in LR < 10 sr and LR > 40 sr and LCDR < 0.3. (See section 4.2 Cirrus optical properties).

It is a good question and I added the answer to the discussion. I copy the paragraph.

"On the other hand, visible and opaque cirrus clouds control the blue sector. The percentage of cirrus found in this area is 12%. As one cloud type does not predominate, the geometrical properties of this subgroup have been analysed, showing an average of cloud base temperature of -41.32±8.62 ºC, being lower to the homogeneous nucleation temperature of -38.15 ºC, (Tanaka and Kimura, 2019) and making the presence of aqueous content in these cirrus clouds impossible. However, eight cases have been found with a temperature above -38.15ºC and an average cloud base height of 7.91±0.68 km. Therefore, in these eight cases the presence of liquid water cannot be ruled out. Except for these 8 cases, the validation of the cloud identification criteria proposed in this study can be successfully concluded."

In this case, thanks to your question, I have rethought my analysis. Now the analysis has been changed and is based on the cloud base temperature. It is true that if the cloud base temperature is higher than the homogeneous nucleation temperature, the presence of liquid water in the cloud cannot be ruled out. Therefore, it has been concluded that, except for 8 cases, the presence of aqueous content in the rest of the cirrus clouds analysed has been ruled out, thus validating the identification of cirrus clouds proposed in this study.

Line 482:

I suggest focusing on the warmest temperature within the cloud (i.e. cloud base) for this determination, rather than mentioning altitude.

I accept your suggestion and now the analysis has been changed and is based on the cloud base temperature. I explained in the previous comment.

Line 499:

"It could be said" is vague. Just state the result.

Right, it was changed.

Line 502:

No weather patterns were examined, so this should not be a conclusion. Rather, it is a hypothesis about the differences between sites. The latitudinal dependence does not seem significant.

Right, the variability at each site is high.

Line 507:

The average height of cirrus is probably not 1.1 km.

Right, it is 11 km. Sorry for the mistake.

Lines 510-517:

This is too long for the conclusions and repeats information. Moreover, several hypotheses about the cause of the results are presented as strong conclusions. For example, the lidar ratio increases with COD because of turbulence). Turbulence was not measured and this attribution cannot be concluded. The linear depolarization does not appear to have any relationship. Certainly, there isn't any cause to attribute any relationship to increases in aggregation, as opposed to e.g. micro-facet roughness of the crystals.

Ok, I accept the suggestions and I changed the conclusion. I copy the entire conclusions.

"In this study, the cirrus geometrical and optical properties of 5 years of continuous ground-base lidar measurements with the Barcelona MPL was analysed, applying the two-way transmittance method. First, a review of the literature on the two-way transmittance method which provides cirrus cloud retrievals like the cloud optical depth, the columnar cloud lidar ratio or the vertical profile of the particle backscatter coefficient was presented. The different approaches that have been developed along the year and the main advantages and disadvantages of this method were also explained. For example, one of the major advantages of this new approach of the method was that it is only necessary to assume a Rayleigh zone both above and below the cirrus cloud, without making any priori optical and/or microphysical hypotheses about the cirrus cloud. Second, a simple mathematical development of the two-way transmittance method for ground-based and spaceborne lidar systems was proposed and was first illustrated for a cirrus cloud in Barcelona, using measurements from the MPL and CALIOP lidars. The results of the two-way transmittance method fitted really well, obtaining a difference of COD for the same cirrus cloud of 0.0215. Third, a set of criteria for cirrus clouds identification was established, which consists of Tbase < -37ºC and CBH > 7 km, and was compared with the literature. After having carried out the identification of 367 high-altitude cirrus clouds, measured with the MPL in Barcelona, from November 2018 to September 2022, the two-way transmittance method has been applied successfully to the 55% of the all cases. Unsuccessful cases were due to the impossibility to guarantee a Rayleigh zone below and above the cirrus cloud, a negative COD and/or a LR higher than 100 sr. Also, it could be observed that the efficiency of the method decreases notably in summer and during the other seasons it remains relatively stable. The cirrus geometrical and physical properties were: CT = 1.8±1.1 km, Tm = -51±8ºC, COD = 0.36±0.45, LR = 30±19 sr and LCDR = 0.32±0.13, with the highest occurrence in spring. It has been seen that in the warmer seasons, opaque cirrus were more frequent than visible cirrus. In addition, these properties were compared to the literature, obtaining similar properties in nearby latitudes, with a majority of visible and opaque cirrus clouds being present. Forth, it was found that the efficiency of the two-way transmittance method and the properties of the cirrus clouds were not dependent on the hour of day and their properties were analysed according to the COD. Resulting in that the subvisible cirrus clouds were the highest, coldest and thinnest clouds; the visible cirrus clouds were the predominant and the opaque cirrus clouds were the lowest, warmest and thickest clouds in the whole cirrus dataset. It has also been seen that the cloud top height did not vary considerably depending on the type of cloud, since the cirrus clouds might reach to/near the tropopause, being its average height of 11±1 km during the cirrus scenes. The correlations between the different cirrus properties were then analysed and quantified for the first time, being the highest correlation R2=0.26 between Tbase and COD. The analysis showed that the COD correlates positively with the cloud base temperature, lidar ratio and linear cloud depolarization ratio and negatively with the cloud base height. Finally, the dependence of LCDR on COD and LR was studied and it was concluded on one hand, that cirrus clouds with LCDR values lower than 0.3 and LR lower than 10 sr were mostly sub-visible cirrus clouds and as a consequence, the possibility of liquid water in them was ruled out. On the other hand, the majority of cirrus clouds with LCDR values lower than 0.3 and LR higher than 40 sr, except 8 cases, had a cloud base temperature lower than the homogeneous nucleation temperature, making impossible the presence of liquid water. Except for these 8 cases, the validation of the cloud identification criteria proposed in this study could be successfully concluded. All this information presented in this work could be of great use for gaining a better understanding of the properties of cirrus clouds, their spatial distribution at the global scale and the key processes which govern cirrus formation and evolution. This study could also help development of new parameterizations of cirrus clouds to obtain their optical, microphysical and radiative properties and development of cirrus cloud products obtained with spaceborne or ground-based lidar instruments."