Response to Reviewer 3:

We sincerely thank the reviewer for the very careful, detailed, and constructive review of our manuscript. We greatly appreciate the time and attention devoted to the paper. The comments were particularly useful in identifying aspects of the methodology and presentation that were not sufficiently clear in the original version, especially regarding the Young inversion, the distinction between the different iterative steps, the definition of the statistical sampling, and the interpretation of the Young-compatible subset.

In response to these comments, we have substantially revised the manuscript. We reorganized the methodology section, added a dedicated subsection explaining the Young inversion principle and implementation, introduced a step-by-step description of the processing chain, clarified the definition of the main variables and of "cloud layers", and revised several parts of the Results and Discussion to avoid overinterpretation of statistically limited subsets. We also improved the terminology throughout the manuscript and added additional context from previous ground-based and satellite lidar studies. We believe that these changes have significantly improved the clarity, robustness, and readability of the paper.

A detailed point-by-point response is provided below. The reviewer's remarks are reported in *italics* and with a different indentation from our responses, while the modified text of the manuscript is reported in red.

Major comments

1. *The Young inversion method is not sufficiently explained in the methodology section. The current description is vague and would benefit from a dedicated paragraph clearly reminding of the principles of the method, its assumptions, and its implementation in this study. Please explain what it does, based on given inputs and outputs.*

We have added a dedicated subsection entitled "Young inversion principle and implementation". This subsection now explicitly states the input quantities, the output LR, the physical assumption of equal particle backscatter ratio immediately above and below the cloud, and the iterative procedure used to find the LR that minimizes the top-bottom mismatch in the corrected backscatter ratio.

Young inversion principle and implementation

The Young inversion is an elastic-lidar method used to estimate the layer-mean lidar ratio of a cloud when an independent Raman extinction measurement is not available. The input quantities are the attenuated backscatter ratio profile, the molecular backscatter and extinction profiles, and the cloud base and top heights. The unknown quantity is the cloud lidar ratio, $LR = \alpha_{\mathrm{p}}/\beta_{\mathrm{p}}$, which is assumed to be constant within the detected cloud layer.

The method is based on the assumption that, after correction for the extinction produced by a vertically homogeneous cloud, the particle backscatter ratio immediately below and above the cloud should be the same. For a trial value of LR, the attenuated backscatter profile is corrected for particle extinction inside the cloud and the corrected backscatter ratio R_{cor} is computed. The optimal LR is the value that minimizes the absolute difference between the mean R_{cor} values in two cloud-free reference windows located below and above the cloud. In this study, the reference windows are 240 m thick and are offset by 180 m from the cloud boundaries.

At each trial value of LR, a short internal iteration is performed: R is updated inside the cloud, the particle-extinction correction is recomputed, and the top-bottom consistency is evaluated again. The process converges rapidly, yielding the LR that best satisfies the Young condition. The retrieved LR is therefore a layer-mean quantity and should be interpreted as an effective optical property of the whole cloud layer, rather than as a vertically resolved lidar-ratio profile.

2. The wording throughout the manuscript is sometimes overly complex or not aligned with standard terminology in the lidar community. The authors are encouraged to improve clarity by simplifying and using standardize the language. Examples include:

"polarization diversity Rayleigh lidars" → "elastic backscatter lidar with depolarization capability"

"extinction corrections" → "extinction retrievals'

We agree and have revised the terminology throughout the manuscript. In particular, we replaced "polarization diversity Rayleigh lidar" with "elastic backscatter lidar with depolarization capability" where appropriate, and we revised ambiguous expressions such as "extinction correction" to distinguish between provisional extinction correction used for cloud-boundary detection and extinction retrieval/correction within the Young inversion.

3. Key variables (e.g. R_{fixed}, R_{cor}) are not clearly defined when first introduced. A clear and consistent definition of all symbols and acronyms is necessary.

We have added explicit definitions at first occurrence. R_{att} is the attenuated backscatter ratio after molecular normalization but before particle-extinction correction. R_{fixed} is the provisional backscatter ratio obtained after applying a fixed LR of 30 sr only for cloud-boundary detection. R_{cor} is the backscatter ratio corrected using a trial LR during the Young inversion. The final retrieved quantity is the layer-mean LR minimizing the top-bottom mismatch in R_{cor}.

4. The description of the methodology, particularly the iterative procedures involved in the LR retrieval, is difficult to follow. It appears that multiple iterative processes are used (e.g. cloud boundary detection and Young inversion), but these are not clearly distinguished. A schematic diagram or a step-by-step description of the full processing chain would greatly improve readability.

We agree that the previous description did not sufficiently distinguish the two iterative steps. We have therefore restructured the methodology and added a step-by-step flowchart at the beginning od the "Data Processing and Methodology" Section. . The first iteration is used only to detect stable cloud boundaries after applying a provisional fixed LR. This provisional correction is discarded after the boundaries are defined. The second iteration is the Young inversion itself, in which a trial LR is varied until the corrected backscatter ratio above and below the cloud becomes consistent.

The processing chain in the text is now organized as follows:

1. dark-count subtraction and range correction;

2. merging of tropospheric and stratospheric channels;

3. molecular normalization and depolarization calibration;

4. provisional extinction correction using $LR = 30$ sr;

5. iterative cloud-boundary detection on R_{fixed};

6. removal of the provisional correction;

7. Young inversion on the original attenuated profile;

8. selection of the Young-compatible subset using external homogeneity criteria;

9. optical weighting and statistical aggregation by cloud class.

5. The results are mainly compared to literature values. The manuscript would be significantly strengthened by including an independent evaluation, for example through comparison with satellite observations such as CALIOP *(on CALIPSO mission, for the data until June 2023) or ATLID (on EarthCARE mission, for the data starting mid-2024), particularly for the year 2024 if data are available.*

We agree that an independent comparison with spaceborne lidar observations would strengthen the interpretation of the results. We have therefore revised the Discussion to place the present LR retrievals in the context of previous statistical comparisons between the Concordia ground-based lidar record and CALIOP observations.

A direct quantitative validation of the retrieved LR values with CALIOP or ATLID is not straightforward, because it would require strict temporal and spatial collocation, consistent cloud-boundary definitions, comparable extinction/backscatter retrieval assumptions, and, in the case of ATLID, a treatment of the wavelength difference between the 532 nm measurements analysed here and the 355 nm ATLID observations. For this reason, we did not introduce a new event-by-event satellite validation of LR in the present revision.

However, the statistical consistency between ground-based lidar observations at Concordia and CALIOP PSC observations has already been investigated by Snels et al. (2021). That study compared the statistical occurrence and composition of PSCs observed from the ground with those derived from CALIOP over the same Antarctic sector, showing that the Concordia lidar record is broadly consistent with the spaceborne climatology at the level of PSC occurrence and microphysical classification. A similar study was carried out for lidar observatons at McMurdo Station. We have added a paragraph in the Discussion to clarify this point.

The present study builds on that statistically consistent observational framework, but addresses a different problem: the retrieval of layer-mean LR from the ground-based elastic lidar using the Young inversion. We now explicitly present the LR dataset as a ground-based statistical reference that may support future dedicated collocation studies with CALIOP legacy products and EarthCARE/ATLID observations, rather than as a completed satellite LR validation.

In the Discussion we have added:

The present analysis does not include a direct satellite-based validation of the retrieved LR values. Such a comparison would require strict temporal and spatial collocation, consistent cloud-boundary definitions, and a careful treatment of the different retrieval assumptions used by ground-based elastic lidar and spaceborne lidar products. In the case of ATLID/EarthCARE, an additional complication is the wavelength difference between the 532 nm measurements analysed here and the 355 nm ATLID observations. However, the statistical consistency between the Dome C ground-based lidar record and CALIOP PSC observations has already been assessed. Snels et al. (2021) compared the statistical occurrence and composition of PSCs observed at Dome C with CALIOP observations over the same Antarctic sector, showing that the ground-based record is broadly consistent with the spaceborne PSC climatology in terms of occurrence and microphysical classification. A similar comparison was carried out for the PSC observed at McMurdo Station (77 50'S, 166 40'E; 183 m a.s.l.) (**??**). The LR climatology presented here therefore builds on an observational framework whose statistical representativeness has already been documented, while extending it by providing layer-mean LR estimates from the ground-based Young inversion. These values may serve as a ground-based statistical reference for future dedicated collocation studies with CALIOP legacy products and EarthCARE/ATLID observations.

In the Conclusion we have substituted the last two sentences with:

The LR statistics presented here also provide a useful ground-based statistical reference for the interpretation of spaceborne lidar observations. This is particularly relevant in view of the CALIOP legacy PSC record and of the current EarthCARE/ATLID mission. Previous statistical comparisons at Dome C have shown that the ground-based lidar record captures PSC occurrence and composition features broadly consistent with CALIOP-based Antarctic climatologies. The present study extends this framework by adding observational constraints on layer-mean LR.

6. *Abstract: One important result of the comparison between Young-derived and full-dataset LR retrievals, is the cloud variability and mixing. This could be highlighted in the abstract.*

We have added the following text to the abstract

The comparison between the full dataset and the Young-optimized subset shows that the retrieved LR statistics are not controlled only by particle type, but also by cloud structural complexity and mixing. In particular, ice PSC and some cirrus layers frequently violate the vertical homogeneity assumptions of the Young method, so that their layer-mean LR should be interpreted as an effective value representative of mixed or vertically structured clouds rather than as a pure microphysical signature.

Minor comments

1. *Line 32 (and throughout): "LR in the range 40–70 sr": please specify the wavelength.*

Corrected there and elsewhere.

2. *Line 35: "S = 40 sr": ensure consistency in notation for the lidar ratio throughout the manuscript. In most of the paper lidar ratio appears to be denoted as LR.*

Done.

3. *Line 52: "extinction correction": consider using "extinction retrieval," which is more standard terminology.*

Done.

4. *Line 56: "physically based alternative": please clarify what is meant by "physically based."*

We agree that the expression "physically based alternative" was too generic. We have clarified the sentence in the Introduction. By "physically based" we meant that the Young inversion does not prescribe a fixed lidar ratio from an external climatology, but estimates an effective layer-mean LR by imposing a physical consistency condition on the extinction-corrected backscatter profile, namely that the particle backscatter ratio immediately below and above a homogeneous cloud layer should be the same. We have revised the wording accordingly. Now the sentence reads:

A physically constrained alternative is the Young inversion method (Young, 1995; Young and Vaughan, 2009), which estimates an effective layer-mean LR directly from the measured elastic-lidar profile by imposing top-bottom consistency of the particle backscatter ratio after correction for cloud extinction.

5. *Line 60: "not yet fully characterized": if previous studies exist, they should be cited to properly position this work.*

To the best of our knowledge, no previous study has provided a multi-year, ground-based determination of layer-mean LR for both PSC microphysical classes and tropospheric cirrus in polar regions using a uniform Young-inversion framework. Previous Concordia studies have documented PSC occurrence, optical properties, and classification in the backscatter-depolarization phase space, and these studies are cited more explicitly to position the present work. We have revised the sentence to avoid the overly broad statement "not yet fully characterized" and to specify more precisely the gap addressed by this manuscript. We have added the following: While previous Concordia studies have documented PSC occurrence and optical classification in the backscatter-depolarization phase space (Snels et al, 2021, Di Liberto et al, 2024), a multi-year, ground-based determination of layer-mean LR for the main PSC microphysical classes and tropospheric cirrus using a uniform Young-inversion framework has not yet been reported for this site.

6. Line 60: Dome C is mentioned for the first time. Consider adding a brief description (e.g. altitude, Antarctic Plateau context), so that the reader can better follow the subsequent paragraph.

We have added a brief description of the Dome C site at its first occurrence in the Introduction, specifying that Concordia Station is located on the East Antarctic Plateau at about 3233 m a.s.l. This should help the reader understand why the site is particularly suitable for long-term PSC and cirrus observations.

7. Lines 62–63 vs 87–88: Some repetition is present

See the following point 8.

8. Section 2.1: The section "Concordia Station" includes extensive discussion of lidar characteristics. Consider splitting into subsections (e.g. '…Dome C, located at 3km a.s.l on an ice dome on the East Antarctic Plateu'). Then you can continue with the next paragraph which provides more information on the conditions.

We agree with the reviewer. In the revised manuscript, we removed the repetition between the end of the Introduction and Sect. 2.1. The first mention of Dome C in the Introduction now contains only a concise description of the site and its relevance for polar cloud observations. The more detailed information has been moved to Sect. 2.

We also reorganized Sect. 2 by separating the description of the observing site from that of the lidar system. The section now includes two subsections: "Concordia Station and observing conditions", which describes Dome C and the environmental context, and "Lidar system", which describes the instrumental configuration, acquisition channels, vertical resolution, temporal integration, and measured quantities.

9. Line 93: What is the maximum range of the lidar?

We have clarified the instrumental range in Sect. 2.2. The lidar signal can be used for atmospheric sounding up to about 50 km under suitable conditions, whereas the processed dataset analysed in this work is limited to the altitude range below 30 km, which fully covers the tropospheric cirrus and PSC layers considered here. We have added to the text the following:

The lidar sounding can extend up to about 50 km under suitable conditions. In the present analysis, however, the processed profiles are restricted to altitudes below 30 km due to signal-to-noise constrains. This fully covers the altitude range of the cirrus and PSC layers investigated in this study.

10. Line 94: "which is the normal procedure": clarify if this refers to 32-minute averaging or to some other aspect.

We thank the reviewer for noting this ambiguity. The expression "which is the normal procedure" referred to the standard temporal averaging used in our processing, namely the averaging of 16 consecutive 2-min recordings to obtain an effective temporal resolution of 32 min. We have revised the sentence to make this explicit. Now the sentence reads:

The effective vertical resolution of the processed profiles is 30-60 m, depending on the acquisition configuration. The basic acquisition time is 2 min; in the standard processing used for this study, 16 consecutive recordings are averaged, yielding an effective temporal resolution of 32 min.

11. Section 3: Consider splitting into subsections such as "Lidar processing" and "Young inversion."

We agree with the reviewer. Section 3 has been reorganized into separate subsections to improve readability and to distinguish the different processing steps. In particular, the revised section now separates lidar preprocessing and calibration, cloud-boundary detection, the Young inversion itself, and the selection of Young-compatible cloud layers. This restructuring also helps distinguish the preliminary iterative procedure used to define cloud boundaries from the Young inversion used to retrieve the layer-mean LR.

12. Line 128: "uncertainty profiles are smoothed": specify the smoothing scale and method (e.g. 300 m moving window?).

We thank the reviewer for pointing out this missing detail. We have clarified that the uncertainty profiles are smoothed using the same moving-average approach adopted for the signal profiles, with a 300 m vertical window. This smoothing is applied only to reduce bin-to-bin noise in the uncertainty estimate and does not modify the cloud-boundary detection criteria. We have reformulated the sentence as:

Statistical uncertainties are computed assuming Poisson counting statistics. The resulting uncertainty profiles are smoothed with a 300 m vertical moving-average window to reduce bin-to-bin noise and are stored as part of the final data product.

13. Line 132: "weighting function produces a smooth transition": specify the altitude range over which gluing is applied.

We have specified the altitude interval over which the tropospheric and stratospheric acquisition channels are merged. The gluing is performed using an altitude-dependent weighting function over the overlap region between the two channels, from 8 to 12 km. This information has been added to Sect. 3.1. Now the sentence reads:

An altitude-dependent weighting function is applied over the overlap region between 8 and 12 km to produce a smooth transition between the tropospheric and stratospheric channels and to ensure continuity of the merged profile.

14. Lines 139–143: Given known calibration issues (e.g. Di Liberto et al 2024), it would be helpful explain why the depolarization calibration is important, before describing the procedure.

We have added a short explanatory paragraph before describing the calibration procedure. The revised text now clarifies that depolarization calibration is essential because PSC classification relies directly on the measured depolarization signal: STS droplets are nearly spherical and weakly depolarizing, whereas NAT and ice particles are non-spherical and produce stronger depolarization. Therefore, even small instrumental cross-talk between the parallel and cross-polarized channels may lead to biases in the derived depolarization ratio and, consequently, in the microphysical classification. We also explicitly refer to Di Liberto et al. (2024), where the Concordia lidar polarization calibration and the role of optical cross-talk, including the contribution from the observatory viewport, are discussed in detail. The following text has been added:

The depolarization calibration is a critical step for the present analysis because the separation of PSC microphysical classes relies directly on the measured polarization state of the backscattered signal. Nearly spherical STS droplets produce very weak depolarization, whereas non-spherical NAT and ice particles produce significantly larger depolarization. Any instrumental leakage between the parallel and cross-polarized channels may therefore bias the retrieved depolarization ratio and, in turn, affect the attribution of cloud points to STS, NAT or ice classes. This is particularly important for the Concordia lidar system, for which optical cross-talk contributions, including those associated with the optical viewport, have been discussed in detail by Di Liberto et al. (2024).

Accurate polarization measurements require correction for optical and electronic crosstalk (CT) and for the gain ratio $G \approx g_{\parallel}/g_{\perp}$ of the detection channels, where $P_{\parallel,\perp} \sim g_{\parallel,\perp}\beta_{\parallel,\perp}$. Following the molecular-consistency approach originally proposed in Di Liberto et al. (2024), the calibration relies on the fact that in purely molecular layers the ratio of the gain-normalized and cross-talk-corrected cross-polarised to the parallel backscatter must equal the known molecular depolarisation δ_{mol}, which in our case, given the characteristics of the lidar, is 0.007 (Behrendt et al., 2002).

15. Line 144: Symbol usage may be misleading compared to standard conventions (e.g. Freudenthaler et al., 2016 that uses G for cross-talk). Please ensure consistency.

We thank the reviewer for pointing out the possible ambiguity, which we acknowledge. We agree that different polarization-lidar calibration formalisms use different symbol conventions. In the present manuscript, we retain G for the gain ratio between the parallel and cross-polarized detection channels and CT for the cross-talk coefficient, because this notation is used consistently in our processing code, in the derivation adopted here, and in the previous description of the Concordia lidar calibration by Di Liberto et al. (2024). To avoid confusion with other conventions, including those in which G denotes a cross-talk or calibration matrix term, we have revised the text to define both quantities explicitly at their first occurrence and to use the notation consistently throughout the manuscript. We did not change the symbols themselves, but clarified the convention to prevent confusion with other polarization-lidar notations. We have thus added the following:

In the notation used here, consistently with the Concordia lidar calibration described by Di Liberto et al. (2024) , G denotes the gain ratio between the parallel and cross-polarized detection channels, $G = g_{\parallel}/g_{\perp}$, whereas CT denotes the cross-talk coefficient representing leakage from the parallel into the cross-polarized channel. This convention is adopted consistently throughout the manuscript.

16. Line 167: "attenuation-induced curvature of Ratt": this wording is unclear and should be clarified.

We agree that the expression "attenuation-induced curvature of R_{att}" was unclear. We have revised the sentence to state more explicitly that extinction within the cloud attenuates the signal from the upper part of the layer and from the atmosphere above it. As a consequence, the attenuated backscatter ratio may show an artificial vertical decrease or deformation that can obscure the true cloud-base and cloud-top gradients. The provisional correction with a fixed $LR = 30$ sr is used only to reduce this attenuation effect and improve the detection of cloud boundaries. The sentence now reads:

This choice is not meant to reflect the true cloud optical properties. It is used only to partially compensate for the signal attenuation produced by cloud extinction, which can distort the vertical shape of R_{att} and obscure the gradients associated with cloud base and cloud top.

17. Line 178: Is the choice of 240 m window size and 180 m offset based on some criteria? Please answer the question in the paper.

We thank the reviewer for this comment. We have clarified the rationale for the choice of the reference windows. The 180 m offset is used to avoid the bins immediately adjacent to the detected cloud boundaries, where uncertainties in cloud-edge detection, smoothing, partial attenuation correction, or gradual transitions may contaminate the reference signal. The 240 m window thickness provides a compromise between using a layer close enough to the cloud to represent the local background and including enough vertical bins to obtain a stable mean R_{cor}. These values were selected empirically after sensitivity tests on representative profiles and were found to provide stable Young inversions without sampling regions too far from the cloud. We have added the following text:

The offset and window thickness were chosen as a compromise between locality and statistical stability. The 180 m offset avoids the range bins immediately adjacent to the detected cloud boundaries, where uncertainties in cloud-edge location, smoothing, residual attenuation effects, or gradual cloud-background transitions may affect the signal. The 240 m window thickness provides enough vertical samples to compute a stable mean R_{cor}, while remaining close enough to the cloud to represent the local background conditions above and below the layer.

18. Lines 164–181: The processing steps are difficult to follow. A diagram or structured description is recommended.

As already reported in the answer to Point 4. in the Major Comments, to improve readability, we have restructured Sect. 3 and added a step-by-step summary of the full processing chain at the beginning of the section, before the detailed methodological subsections. This structured description explicitly distinguishes the preliminary iteration used for cloud-boundary detection from the Young inversion itself. We also indicate which steps belong to preprocessing and calibration, which are used only for boundary definition, and which are related to the final LR retrieval and statistical analysis.

19. Line 199: "180 ms" → likely "180 m".

Done.

20. Lines 213–215: The meaning is unclear; please improve text for clarity.

We agree that the sentence was unclear. We have rewritten it to state more directly that the thresholds are empirical and are intended only to identify cases that better satisfy the Young assumptions. The revised text clarifies that moderate changes in the thresholds do not alter the main effect of the filtering: retaining vertically simple cloud layers and excluding clouds embedded in variable backgrounds or characterized by strong internal inhomogeneity. The rephrased text now reads:

Although the numerical thresholds adopted here are necessarily empirical, their role is only to identify cloud layers for which the Young assumptions are more closely fulfilled. Moderate variations of these limits do not change the main effect of the filtering: the preferential retention of vertically simple layers and the exclusion of clouds embedded in highly variable backgrounds or characterized by strong internal inhomogeneity, for which a single layer-mean LR would not provide a fully self-consistent extinction correction.

21. Lines 232–243: Have the authors considered including a cloud thickness criterion to improve classification? Please answer the question in the paper.

We thank the reviewer for this useful comment. A minimum geometrical thickness criterion is already applied during the cloud-detection step to reject very thin or noisy fragments before the Young inversion is performed. However, we did not use cloud thickness as an additional criterion for the microphysical classification. The classification is intentionally based on optical quantities, namely backscatter ratio, depolarization, and altitude relative to the tropopause, because cloud thickness is not uniquely related to particle phase. For example, thin layers may correspond to NAT, ice PSC, or cirrus depending on their optical signature, while vertically extended layers may contain mixed or externally layered particle populations. We have added a clarification in the manuscript explaining that the thickness criterion is used for robust cloud detection, but not for assigning PSC or cirrus microphysical class. To clarify this, we have added in the text the following:

A minimum geometrical thickness criterion is applied during the cloud-detection step to reject very thin or noisy fragments before the Young inversion is performed. However, cloud thickness is not used as an additional microphysical classification criterion. The classification is intentionally based on optical quantities, namely backscatter ratio, depolarization and altitude relative to the tropopause. This choice avoids introducing a geometrical constraint that is not uniquely related to particle phase: thin layers may correspond to NAT, ice PSC or cirrus depending on their optical signature, whereas vertically extended layers may contain mixed or externally layered particle populations.

22. Line 272: What is the minimum number of points required per bin? Please answer the question in the paper.

We thank the reviewer for pointing out this missing information. We have now specified the minimum-count criterion used in the two-dimensional phase-space maps. In the present analysis, bins are displayed when they contain at least one optically weighted range-time sample; empty bins are left blank. We also clarified that this threshold is used only for visualization of the phase-space maps and should not be interpreted as defining the number of independent LR retrievals. The independent statistical unit remains the detected cloud layer, whereas the two-dimensional maps are used to show where the optically dominant portions of the cloud population lie in the $(1-1/R, \delta_T)$ space. To clarify this, we have now n the text:

In the two-dimensional maps, bins are retained when they contain at least one optically weighted range-time sample, while empty bins are left blank. This criterion is used only for visualization and does not alter the statistical definition of the dataset: the independent retrieval unit remains the detected cloud layer.

23. Line 297: “emanating” → consider “extending.”

Done.

24. Lines 319–321: Have the authors tested relaxing the selection criteria to increase the number of Young-compatible layers? Please answer the question in the paper.

We thank the reviewer for this comment on an important aspect, maybe not sufficiently underlined. We explored the effect of relaxing the Young-compatibility criteria. As expected, less stringent thresholds increase the number of retained layers, but they also admit clouds embedded in more variable backgrounds or characterized by stronger internal inhomogeneity. Since the aim of the Young-compatible subset is not to maximize the number of retained cases, but to isolate layers for which the Young assumptions are most closely fulfilled, we retained the stricter criteria in the final analysis, even at the expense of statistical representativeness for some cloud classes. We have clarified this point in the manuscript adding the following lines:

Relaxing the Young-compatibility criteria would increase the number of retained layers, but at the cost of admitting cases with more variable background conditions or stronger internal cloud inhomogeneity. We therefore retained the stricter criteria in the final analysis. This choice favours methodological robustness over statistical representativeness for the Young-compatible subset, particularly for structurally complex classes such as ice PSC and some cirrus layers. The subset should therefore be interpreted as a conservative benchmark rather than as a statistically complete representation of each cloud class.

25. Line 331: "LR increased with both backscatter and depolarization": this statement appears too strong given the observed variability. Looking at the plot I must say that the linear relationship described here is not always the case.

True, the original sentence was too strong and could be interpreted as implying a monotonic or linear dependence of LR on backscatter and depolarization. We have revised the text to make the statement more cautious. The revised version now states that LR tends to be larger in parts of the phase space associated with stronger depolarization and larger backscatter ratios, but that the relationship is not monotonic and shows substantial variability. We have modified the text accordingly, as hereby reported:

For the full dataset, LR tends to be larger in portions of the phase space associated with stronger depolarisation and larger backscatter ratios. However, this dependence is not monotonic and exhibits substantial scatter, reflecting both intrinsic microphysical variability and the occurrence of mixed or vertically structured PSC layers. Typical values range from $\sim 30-50$ sr for STS to $\sim 40-70$ sr for NAT and ice PSC.

26. Line 347: '. . . composed of H2SO4/. . . ', please add citations here.

Thanks for noting this omission. We have added appropriate references for the composition of STS droplets as ternary $H_2SO_4/HNO_3/H_2O$ solutions, citing Carslaw et al. (1995) and Peter and Grooß (2012). In the same paragraph, where we discuss the possible coexistence of STS droplets with nascent NAT particles and the resulting higher-LR mode, we have also added a reference to Cairo et al. (2023), which discusses optical scattering by mixed-phase PSC particle populations. The sentence now reads:

A first peak appears near 35 sr, consistent with classical supercooled ternary solution droplets composed of aqueous sulfuric acid, nitric acid and water (Carslaw et al., 1995, Peter and Grooß, 2012). A second, smaller accumulation emerges around 60 sr. This higher-LR mode may reflect layers where STS droplets coexist with a minor fraction of nascent NAT particles, or more generally mixed-phase PSC conditions, for which optical scattering can differ from that of pure single-component particle populations (Cairo et al., 2023)

27. Line 398: The described oblique lines are not clearly visible.

We have improved the visibility in the new figures.

28. Line 399: "increase" → "increases".

Done.

29. Lines 396-402: The particle backscatter (beta_aer) as well as particle depolarization (delta_a) are discussed in this paragraph but not shown, which makes the description of the plot difficult to follow. Please consider rewriting this paragraph in a way that is easier for the reader to follow what is seen in the figure.

We agree with the reviewer. The previous paragraph referred to particle backscatter and particle depolarization in a way that was not sufficiently clear, since these quantities are not directly plotted in the figure. We have therefore rewritten the paragraph to focus on the quantities displayed in Fig. 5, namely $1-1/R$ and δ_T.

The revised text clarifies that, in the $(1-1/R, \delta_T)$ representation, points distributed along the same oblique direction correspond approximately to clouds with similar particle depolarization but progressively increasing backscatter ratio R. Thus, the main branch observed for cirrus is interpreted as a sequence of observations with comparable particle depolarization and increasing optical contrast. This preserves the physical interpretation of the phase-space structure while avoiding references to variables that are not directly shown in the plot.The full dataset exhibits the expected continuous distribution of tropospheric cirrus in the $(1-1/R, \delta_T)$ phase space. In this representation, the oblique directions are related to approximately constant particle depolarization: moving outward along such a direction mainly corresponds to increasing backscatter ratio R, while the intrinsic depolarizing character of the particles remains broadly similar. Thus, the main branch observed in Fig. 5 can be interpreted as a sequence of cirrus observations with comparable particle depolarization and progressively increasing optical contrast. The cirrus population does not separate into distinct clusters, but rather occupies a continuous domain extending toward larger values of both $1-1/R$ and δ_T. The rewritten paragraph now reads:

The full dataset exhibits the expected continuous distribution of tropospheric cirrus in the $(1-1/R, \delta_T)$ phase space. In this representation, the oblique directions are related to approximately constant particle depolarization: moving outward along such a direction mainly corresponds to increasing backscatter ratio R, while the intrinsic depolarizing character of the particles remains broadly similar. Thus, the main branch observed in Fig. 5 can be interpreted as a sequence of cirrus observations with comparable particle depolarization and progressively increasing optical contrast. The cirrus population does not separate into distinct clusters, but rather occupies a continuous domain extending toward larger values of both $1-1/R$ and δ_T.

30. Line 419: “R 50 sr” → should refer to LR.

Corrected.

31. Lines 438-440: Could the authors say a bit more about this plot? (e.g. what was expected from the literature). Please answer the question in the paper. Also the profile seemed to be relatively constant especially when reading the description of Fig.4, where STS is described constant with height.

We agree with the reviewer. The original description of Fig. 8 was too brief and gave too much weight to a weak vertical tendency. We have revised the text to clarify that the cirrus LR profile is relatively stable with altitude within the observed interquartile variability. We now explicitly compare this behaviour with previous cirrus lidar studies. Giannakaki et al. (2007) found no clear dependence of cirrus lidar ratio on cloud temperature and thickness, while Voudouri et al. (2020) reported that cirrus lidar ratio is generally quite constant with temperature, although with some variability and a slight tendency toward larger values at warmer temperatures. Chen et al. (2002) also reported that lidar ratio values can be somewhat smaller at the highest cirrus altitudes. We therefore revised the manuscript to state that a weak decrease of LR at the highest altitudes may be present, but that the dominant feature of Fig. 8 is the approximate vertical stability of the median LR within the observed variability. It now reads:

The vertical profile of cirrus LR shown in Fig. 8 is relatively stable with altitude when the interquartile variability is taken into account. Median values remain within the range reported by previous visible-wavelength cirrus lidar studies, and no strong monotonic dependence on height is evident. This is consistent with the results of Giannakaki et al. (2007), who found no clear dependence of cirrus LR on cloud temperature and thickness, and with Voudouri et al. (2020), who reported that cirrus LR is generally quite constant with temperature, although with substantial variability. A weak decrease of LR at the highest altitudes may be present, which would not be inconsistent with Chen et al. (2002), who reported lower LR values for cirrus above about 15 km. However, in the present dataset this feature should be interpreted cautiously because of the limited sampling in some altitude bins and the broad variability of cirrus optical properties.

32. Line 440: Typo at the end of line.

Corrected.

33. Line 449: 'An increase in the lidar ratio generally reflects a shift toward larger or more aspherical particles', the authors should clarify whether they are discussing only about cloud particles as certain particle types do not necessarily follow this relation. (e.g. biomass burning).

We agree with the reviewer that the original sentence was too general. We have revised the text only to clarify the scope of the statement. The interpretation is intended for the cloud particle types considered in this study - STS, NAT, ice PSC and cirrus particles - and is supported by modelling studies for these classes. We now explicitly state that this relationship should not be generalized to all atmospheric aerosol types, for which absorption, composition and internal mixing may alter the relationship between particle properties and LR. The paragraph now reads:

For the cloud particles considered in this study, an increase in the lidar ratio generally reflects a shift toward larger or more non-spherical particles. Since the extinction coefficient scales approximately with particle cross-section while the relative backscatter efficiency may decrease for larger, non-spherical or irregularly shaped particles, the ratio α/β increases as particle size increases or morphological complexity changes. Here, morphological complexity refers mainly to deviations from sphericity and to irregular particle shape, rather than to chemical composition. This behaviour is well established in modelling studies for STS (lou et al., 2003), NAT (hoepfner et al., 2006), and ice PSC (Reichardt et al., 2004), where higher LR values correspond to particles with larger effective radii, broader size distributions, or more aspherical shapes. This interpretation is intended for PSC and cirrus cloud particles and should not be generalized to all atmospheric aerosol types, for which absorption, composition and internal mixing may alter the relationship between particle properties and LR. Therefore, the observed increase of LR with altitude for NAT, and the large LR variability of ice PSC, are consistent with the presence of progressively larger or more irregular particles under colder stratospheric conditions.

34. Lines 450–451: "complex particles": please clarify (e.g. shape, composition).

We have clarified the expression "more complex particles" in the preceding answer. In this context, we did not refer primarily to chemical complexity, but to particle morphology, in particular non-sphericity and irregular shape. The text reported above has been revised to state more explicitly that, for the cloud particles considered here, increasing non-sphericity or irregularity can reduce the relative backscatter efficiency compared with extinction, thereby increasing the lidar ratio.

35. Line 466: In addition to LR shifts, the presence of multiple modes in Young retrievals appears important and could be discussed. Also should discuss a bit more in the text whether this modes are realistic.

We agree with the reviewer that the apparent multimodal structure in some Young-compatible LR distributions deserves a more cautious discussion. In the original version, the possible physical interpretation of these modes was maybe stated too strongly. We have revised the text to clarify that the observed modes may be physically suggestive, but cannot be considered conclusive evidence for distinct microphysical sub-populations.

In particular, the Young-compatible subset is strongly filtered and contains a reduced number of layers, especially for ice PSC and cirrus. Therefore, apparent secondary modes may arise from a combination of real microphysical variability, selection effects introduced by the homogeneity criteria, and limited sampling. We now explicitly state that the bimodality observed for STS and NAT should be interpreted as a hypothesis-generating feature rather than as a robust climatological result. A more definitive assessment would require a larger number of Young-compatible cases or independent microphysical constraints. We have changed the text accordingly.

In the section Results, commenting Fig. 3, the text now reads:

In the Young–optimized subset, the LR distributions become markedly narrower for STS and NAT, while ice PSC nearly disappear because their edges typically show strong vertical inhomogeneities in both backscatter and depolarisation, causing them to fail the Young homogeneity and symmetry constraints. STS retain values around 41 sr (31–61 sr), but their distribution shows a weak apparent bimodality. A first accumulation appears near 35 sr, which is consistent with classical supercooled ternary solution droplets composed of aqueous sulfuric acid, nitric acid and water (Carslaw et al., 1995, Peter and Grooss, 2012). A second, smaller accumulation occurs around 60 sr. This higher-LR feature may reflect layers in which STS droplets coexist with a minor fraction of nascent NAT particles, enhanced droplet growth under very cold conditions, or more generally mixed-phase PSC conditions, for which optical scattering can differ from that of pure single-component particle populations (Cairo et al., 2023). However, given the limited number of Young-compatible layers and the selectivity of the filtering criteria, this secondary accumulation should be interpreted cautiously.

NAT also shows an apparent multimodal structure, with one accumulation around 40 sr and another around 65–75 sr. Such a structure could be consistent with different NAT particle populations, for example smaller weakly depolarising particles and larger or more aspherical particles forming under colder conditions. However, the available sample does not allow us to demonstrate that these accumulations represent distinct and robust microphysical regimes. They may also be influenced by the Young selection criteria, residual vertical inhomogeneity, or limited sampling. We therefore interpret the multimodal behaviour as a suggestive feature of the Young-compatible subset, rather than as a definitive climatological result.

The ice PSC distribution in the Young subset is extremely compressed (32–38 sr), indicating that only marginal cases survive the selection, as their strong vertical gradients and likely external mixing with other PSC classes make them generally incompatible with the Young inversion constraints. Overall, the main robust result of the Young-compatible subset is therefore not the exact position of individual modes, but the narrowing of the LR distributions for the more homogeneous STS and NAT layers and the strong reduction of structurally complex ice PSC cases.

In the Discussion, the text now reads:

The Young–optimized subset selectively removes layers where the Young inversion is more likely to fail. Its effect differs among PSC classes. For STS and NAT, the filtering mainly narrows the LR distributions and shifts the median values to:

$$LR_{\mathrm{STS}} \approx 41 \text{ sr}, \qquad LR_{\mathrm{NAT}} \approx 61 \text{ sr}.$$

For ice PSC, however, the number of retained layers becomes too small to define a representative lidar-ratio statistic. The apparent decrease of the ice-PSC median LR in the Young-compatible subset should therefore not be interpreted as a robust microphysical result. It more likely reflects the preferential exclusion of vertically structured and mixed-phase ice PSC layers, leaving only a few optically simple or marginal cases.

The apparent multimodal structure observed in the Young-compatible STS and NAT distributions should also be interpreted cautiously. These modes may reflect real microphysical variability, such as different particle sizes, degrees of asphericity, or mixed STS/NAT conditions. However, they may also be affected by the limited number of retained layers and by the selectivity of the Young-compatible criteria. We therefore do not interpret the modes as conclusive evidence for distinct microphysical regimes, but rather as suggestive features that would require larger samples or independent microphysical constraints to be confirmed.

36. Line 521: Typo (“structures .”).

Corrected.

37. Line 530: “real cloud retrievals” → consider “standard retrievals.”

Done.

38. Line 540: The EarthCARE mission is already in orbit (not upcoming).

Corrected.

39. Figures 1, 2, 5, 6: Consider consistently showing classification regions across figures.

Done.

40. Figures 3, 7: Clarify dashed lines in captions (e.g. meaning of distribution).

Done.

41. Table 1: Clarify the definition of "cloud layers," as the numbers do not appear consistent with the number of points shown in the figures.

We thank both reviewers for pointing out this ambiguity. We have clarified the definition of "cloud layers" in the text and in the caption of Table 1. In this work, a cloud layer is defined as one contiguous cloud interval detected in a single lidar profile after the cloud-boundary detection procedure. Each cloud layer is assigned one layer-mean LR by the Young inversion, and therefore represents one independent LR retrieval.

The larger number of points shown in the two-dimensional phase-space figures does not correspond to independent cloud-layer retrievals. Those points are range-time samples within the detected cloud layers, used to display the distribution of the optically weighted cloud population in the $(1-1/R, \delta_T)$ space. We have revised the manuscript to make clear that Table 1 reports the number of independent cloud layers, whereas the figures show optically weighted samples within those layers for visualization and statistical aggregation.

Also in response of reviewer's 1 remarks, we have added the following lines to the "Statistical Analysis" section:

Here, a cloud layer is defined as a contiguous altitude interval classified as cloudy within one lidar profile after the cloud-boundary detection procedure. Each detected cloud layer is assigned a single layer-mean LR by the Young inversion and therefore represents one independent LR retrieval. The larger number of points displayed in the two-dimensional phase-space figures corresponds instead to range-time samples within these cloud layers, weighted according to their aerosol backscatter contribution. These samples are used to describe the optical distribution of the cloud population in the $(1-1/R, \delta_T)$ space, but they should not be interpreted as independent LR retrievals.

While the Table 1 caption now reads:

Number of independent cloud layers contributing to each microphysical class in the full dataset and in the Young-compatible subset. A cloud layer is defined as one contiguous cloudy altitude interval detected in a single lidar profile. Each layer is assigned one layer-mean LR by the Young inversion. The number of cloud layers reported here should therefore not be confused with the larger number of range-time samples displayed in the two-dimensional phase-space figures.