Manuscript ID: acp-2022-56

Original title: CALIPSO Retrieval of Instantaneous Faint Aerosol

Revised title: Retrieving Instantaneous Extinction of Aerosol Undetected by CALIPSO Layer Detection Algorithm

The analysis presented in the manuscript demonstrates the ability to detect "faint" aerosol that is unreported in CALIPSO level 2 retrievals because it lies below feature detection thresholds. The manuscript explains the importance of quantifying this under-represented aerosol based on literature. In order to "detect" the missing aerosol, the authors follow a similar procedure as is used to construct the CALIPSO level 3 stratospheric aerosol product (Kar et al., 2019): cloud and aerosol layers detected by CALIOP are removed from the level 1 attenuated backscatter and then a Fernald retrieval is performed using a fixed lidar ratio. The difference is that the CALIPSO level 3 product reports monthly averages of aerosol extinction, whereas this manuscript analyzes extinction retrieved from individual level 2 granules. This is what is meant by the "instantaneous" descriptor.

The manuscript shows three examples where the CALIOP level 2 algorithms did not detect aerosol layers, but the extinction retrieved by the authors does indicate aerosol enhancement. It goes on to compare their retrieved aerosol extinction values to co-located SAGE III measurements, finding decent correlation at night and a high-bias in their CALIPSO retrievals during the daytime. The logic here is that because their retrieved aerosol extinction at night matches well with SAGE III measurements, then the retrieved aerosol extinction is a fair representation of what was missed by CALIOP level 2 feature detection.

Response: Thank you for your careful review. We have made great efforts to address the issues you raised, and the manuscript has been largely improved. The main changes are as follows.

(1) The title of the paper has been revised as "*Retrieving Instantaneous Extinction of Aerosol Undetected by CALIPSO Layer Detection Algorithm*" to highlight the objectives of the study.

(2) A new method to retrieve lidar ratios by using SAGE III/ISS products as a constraint has been added to the manuscript (see more details in Section 2.4). This study no longer uses the fixed lidar ratio (i.e. 28.75 sr) as in previous study of Kim et al. (2017). We also add a comparison of retrieved undetected aerosol extinction based on globally SAGE-constrained and fixed lidar ratios in Section 3.4 to highlight the effect of the lidar ratio we updated.

(3) Uncertainties in the extinction coefficient retrieval were calculated to assess the

reliability of the extinction results of undetected aerosol. The comparison shows good agreement with the independent SAGE III/ISS aerosol extinction (R=0.66). Especially, the relative uncertainties of the retrieved extinction coefficients at 10^{-3} km^{-1} and 10^{-4} km^{-1} are 35% and 125%, respectively, while the minimum extinction of CALIPSO L2 product is 0.01 km^{-1} with 40% uncertainty (Kacenelenbogen et al., 2011; Toth et al., 2018; Winker et al., 2013; Winker et al., 2009).

(4) The Raikoke eruption event is added to the comparison of instantaneously retrieved undetected aerosol extinction and Level 3 product in Section 3.3.

(5) The results, discussion and conclusions were largely rewritten in the revised manuscript to highlight the significance of this study.

General comments

1. There are some areas where greater details are needed to avoid confusing readers. For example, the manuscript discusses "detectable extinction" by CALIOP multiple times. This is inaccurate because the CALIOP level 2 algorithms do not detect extinction. They detect aerosol layers using attenuated scattering ratio and then perform an extinction retrieval. The minimum "detectable" extinction is really just the minimum extinction occurring within detected aerosol layers. This distinction is important and needs to be made clear. Based on this and my specific comment below about the lack of details regarding CALIPSO vertical resolution, I recommend that the authors provide more information about the details of the CALIPSO level 1 product, and the steps involved in how the level 2 algorithms ultimately retrieve extinction. That would provide important context for the reader.

***Response*:** Thank you for your suggestion. The expression "detectable extinction" has been corrected as you suggested in the revision. Furthermore, a description of the vertical resolution of CALIPSO Level 1 products has been added in Section 2.1, as follows:

(3) The vertical resolution of the CALIPSO Level 1B TAB profiles varies with the height of 30, 60, 120, and 300 m for −0.5–8, 8–20.2, 20.2–30.1, and 30.1–40 km, respectively. Referring to Kim et al. (2017), the TAB profiles are reduced to a vertical resolution of 300 m by linear interpolation to improve the SNR, followed by a vertical moving mean filtering (with a 5-point window) and horizontal averaging to 20 km to retrieve the extinction of undetected aerosol.

The technical process for CALIPSO Level 2 products has also been described, as follows.

The CALIPSO mission introduced new technology for retrieving aerosol profiles from space since April 2006, with a dual-wavelength backscattering lidar as the primary payload (Winker et al., 2010). The CALIPSO team has released different levels of products for different scientific objectives. Level 1 products are calibrated observations containing environmental parameters. Level 2 products are physical, chemical, and optical parameters of aerosol layers and cloud layers obtained according to a series of technical routes. The aerosol and cloud layers are firstly detected by the Selective Iterative Boundary Locator (SIBYL) (Vaughan et al., 2009), then classified by the Scene Classification Algorithms (SCA) (Kim et al., 2018), and finally the extinction coefficient is retrieved according to the Hybrid Extinction Retrieval Algorithm (Winker et al., 2010; Young et al., 2018). Level 3 products provide monthly averaged gridded global distribution data of clouds and aerosols (Kar et al., 2019).

2. The impact of lidar ratio selection is important and inadequately discussed in the manuscript. Two values are used for this analysis (50 sr stratospheric, 28.75 sr tropospheric). The manuscript justifies the two selections for generalized values. However, the aerosol type is known in at least two of the specific cases evaluated: smoke. Since smoke lidar ratios are around 70 sr, this leads to a sizable bias. The manuscript should add a discussion of the limitations of the lidar ratios used by the method.

   Response: Yes, the lidar ratio selection is one of the keys in retrieval. We think about this question very carefully, and develop a new method to retrieve lidar ratios by using SAGE III/ISS products as a constraint, as described in Section 2.4 and follows.

   When using the Fernald method to retrieve aerosol extinction coefficients, the lidar ratio ($S_p(r)$) is a key parameter (Fernald, 1984; Fernald et al., 1972), which is often set based on aerosol type or empirical values (Young et al., 2018; Kar et al., 2019). The backscattered signal of undetected aerosols is extremely weak to be detected and classified by the CALIPSO layer detection and classification algorithms (Kim et al., 2017; Toth et al., 2018). The extinction retrieval of undetected aerosols is very sensitive to the lidar ratio (Kim et al., 2017). Therefore, to obtain the appropriate lidar ratio of undetected aerosol, we retrieve the lidar ratio by using SAGE III/ISS 521 nm AOD as a constraint, and the algorithm flow is shown in Figure 2:

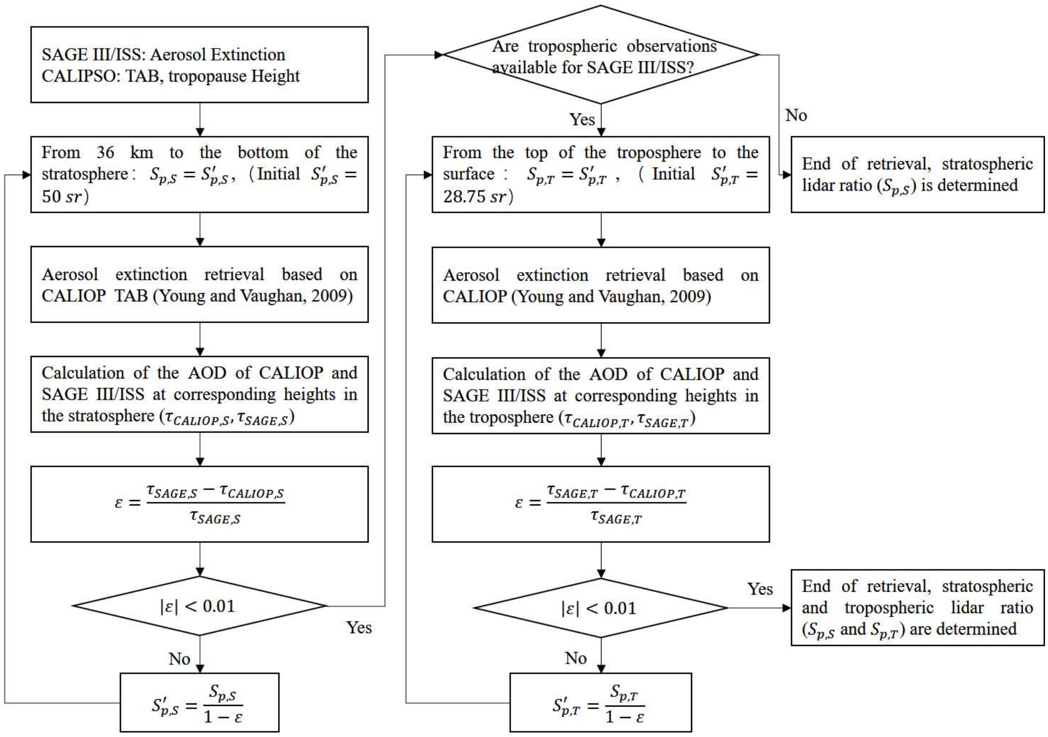

Figure 2. Flowchart for the retrieval of lidar ratio by using SAGE III/ISS AOD as a constraint.

We perform the retrieval of the lidar ratio separately because the aerosol compositions in the troposphere and stratosphere are different. For the stratosphere, the initial lidar ratio ($S_{p,S}$) is set to 50 sr, which is widely assumed for stratosphere aerosol (Kar et al., 2019; Sakai et al., 2016; Khaykin et al., 2017), and the extinction retrieval is performed from 36 km to the bottom of the stratosphere. The AOD of CALIPSO and SAGE III/ISS ($\tau_{CALIOP,\,S}$ and $\tau_{SAGE,\,S}$) for the same altitude bins in the stratosphere and the deviation (ε) between them are calculated. The lidar ratio is iteratively modified and the extinction and AOD of CALIPSO are recalculated until $|\varepsilon| < 0.01$. The same procedure is performed in the troposphere; the difference between the retrieval altitude and using an initial lidar ratio ($S_{p,T}$) of 28.75 sr refers to the estimate by Kim et al. (2017).

The tropospheric and stratospheric lidar ratios are retrieved globally based on matched SAGE III/ISS and CALIPSO profiles and counted at each 20°×20° grid. When performing the extinction retrieval of CALIPSO, $S_{p,S}$ and $S_{p,T}$ can be selected depending on which grid the profile is located on. The constrained retrieval of the lidar ratio uses nighttime CALIPSO and daytime SAGE III/ISS profiles given that daytime CALIPSO observations are affected by solar background noise and have a much lower SNR than nighttime observations (Hunt et al., 2009). The implicit assumption is that diurnal variations in undetected aerosols are ignored. To obtain a consistent lidar ratio retrieval dataset and validation dataset, we used data from the first two months of each quarter to derive the lidar ratio and those of the last month for validation. Thus, for three years from June 2017 to May 2020, 24 months of data are retrieved to determine the lidar ratio and 12 months of data for validation.

Therefore, we get the SAGE-constrained lidar ratio at stratosphere and troposphere in global, respectively, as shown in Figure 3. The lidar ratio is different in the troposphere and stratosphere in global.

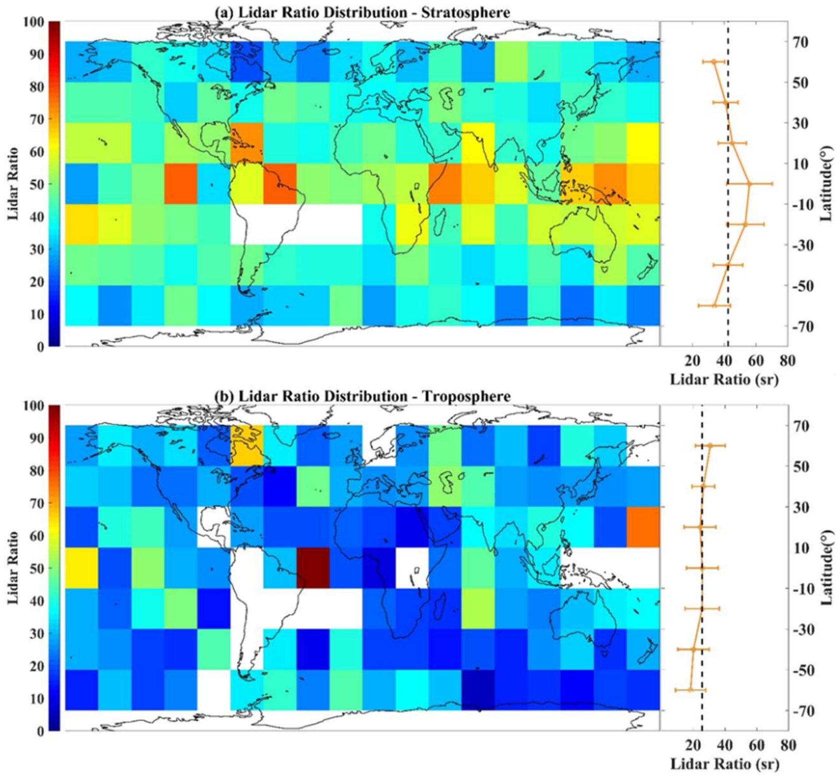

Figure 3. (a) Global stratospheric distribution of lidar ratios with a grid size of 20° x 20°. The color bar represents the lidar ratio value. The line on the right shows the median variation at 20° intervals from −70° to 70° (latitude) globally, and the error bar represents the median absolute deviation. (b) Same as (a), but for the troposphere. A blank grid indicates that no data is available.

Figure 3 shows the global distribution of the median lidar ratios in 20°×20° grids retrieved by CALIPSO under the SAGE III/ISS 521 nm products constraint. The median of the global stratospheric lidar ratio is 42.2 sr, whereas the lidar ratio is smaller at high latitudes than that near the equator (Figure 3a), which is consistent with the latitude-lidar ratio distribution in Kar et al. (2019). The median global tropospheric lidar ratio is smaller (24.5 sr) and shows a different trend from that of the stratosphere, slightly decreasing from the northern to the southern hemisphere (Figure 3b). In the following, we retrieve the extinction of CALIPSO undetected aerosol with the median lidar ratios of the stratosphere and troposphere in the grid, where the CALIPSO profile is located on. In addition, the median absolute deviation of the lidar ratio in the grid is used to calculate the uncertainty of the extinction (Eq. (7)).

Also, the significance of the lidar ratio obtained by this new method and the related bias is also discussed, as follows.

3.4. Discussion on the use of lidar ratio

As mentioned in Section 2.4, the initial stratosphere and troposphere lidar ratios were derived from the empirical value (50 sr) of CALIPSO Level 3 stratospheric aerosol product (Kar et al., 2019) and the lidar ratio (28.75 sr) obtained by Kim et al. (2017), respectively. The latter is estimated from the retrieved CALIPSO column-integrated extinction with MODIS AOD constraints. As shown in Figure 9, the retrieved extinction using the fixed lidar ratio is higher than that using the SAGE-constrained lidar ratio because the median lidar ratio of the former (50 and 28.75 sr) is larger than the latter (42.2 and 24.5 sr). However, the NRMSE of retrieved extinction decreased by about 15% (from 120.2% to 105.6%) when changed the fixed lidar ratio to the SAGE-constrained lidar ratio in global. Particularly, when using the fixed lidar ratio of 50 sr in the high latitude stratosphere, it could result in a larger bias because the fixed lidar ratio is more different from the SAGE-constrained lidar ratio (~35 sr) (Figure 3a). Therefore, these indicate a better accuracy of retrieved undetected aerosol extinction using the SAGE-constrained lidar ratio in global.

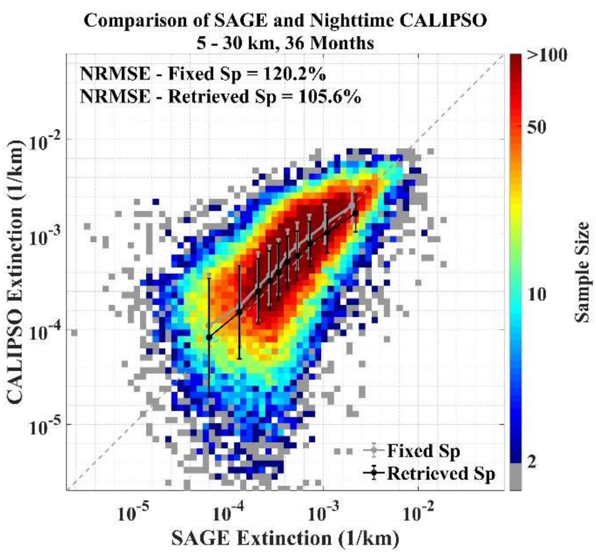

Figure 9. The colored scatter plot is the same as that in Figure 5a, but the CALIPSO extinction are retrieved using fixed lidar ratios of 50 and 28.75 sr in stratosphere and troposphere from June 2017 to May 2020, respectively. The gray and black

lines are the mean value of of each 10% quantile (as in Figure 5a) of the CALIPSO retrieved extinction using the fixed and our retrieved lidar ratios, respectively.

Figure 7b illustrates a possibly missed smoke from a wildfire. Based on the SAGE-constrained lidar ratio (median 42.2 and 24.5 sr), we retrieved and see the undetected aerosol by CALIPSO Level 2 products, which connects with two strong aerosol layers. The lidar ratio for the smoke reported in the CALIPSO Level 2 Version 4 product is 70±16 sr (Young et al., 2018), which is very different from the SAGE-constrained lidar ratio for the troposphere at this location. Theoretically, a larger lidar ratio will derive a larger extinction in the retrieval. This indicates that the undetected aerosol extinction should be larger if using the smoke lidar ratio of 70±16 sr. However, so for, this bias cannot be avoided here because an automatic classification is impossible when we do not know the boundaries of those aerosols. Therefore, we have to treat the stratospheric (or tropospheric) undetected aerosols as a whole and assign the same lidar ratio regardless of the aerosol type in this study. Although the retrieved extinction in Figure 7 is biased, it demonstrated the importance of retrieving high spatial-temporal resolution undetected aerosol extinction. A solution to reduce this bias is to develop a more effective layer detection and classification algorithm, and our team is already working on it (Mao et al., 2021).

3. The conclusions claim to be able to retrieve aerosol extinction down to 0.0001 /km. At that level, however, it is important to consider uncertainty and biases. It is not discussed how large the relative uncertainties are for such small extinction values for the averaging being used. A greater discussion on uncertainties should be added to specify the value the proposed method yields to capturing undetected aerosol.

Response: Thank you very much for your suggestion. To make our conclusion more clear and confident, we have added the calculation of the extinction uncertainty for the retrieval in Section 2.4, as follows:

For the retrieved extinction of undetected aerosol, we calculated the uncertainty to assess the reliability of the results according to the algorithm of CALIPSO Level 2 aerosol product (Young et al., 2013), where the main equations are as follows:

$$\frac{\Delta\beta'_N(r)}{\beta'_N(r)} = \left\{\left[\frac{\Delta\beta'(0,r)}{\beta'(0,r)}\right]^2 + \left[\frac{\Delta C_N\,(r_N)}{C_N\,(r_N)}\right]^2\right\}^{1/2}, \quad (5)$$

$$\left(\Delta\beta_p(r)\right)^2 = \beta_T^2(r)\left[\left(\frac{\Delta\beta'_N(r)}{\beta'_N(r)}\right)^2 + \left(\frac{\Delta T_M^2(r_N,r)}{T_M^2(r_N,r)}\right)^2 + \left(\frac{\Delta T_P^2(r_N,r)}{T_P^2(r_N,r)}\right)^2\right] + \left(\Delta\beta_M(r)\right)^2, \quad (6)$$

$$\Delta\sigma_P(r) = \left[(\frac{\Delta S_p}{S_p})^2 + (\frac{\Delta\beta_p(r)}{\beta_p(r)})^2\right]^{1/2} \sigma_P(r)\,, \quad (7)$$

where $\Delta\beta_p(r)$ and $\Delta\sigma_P(r)$ in Eqs (6) and (7) are the particle backscatter uncertainty and particle extinction uncertainty, respectively; they are the target parameters for the calculation. Eq. (5) is the formula for one of the terms of Eq. (6), where $\Delta\beta'_N(r)$ is the uncertainty of the renormalized TAB, $\Delta\beta'(0,r)$ is the uncertainty of the TAB, and $\Delta C_N\,(r_N)$ is the uncertainty of renormalization. The error due to renormalization is negligible (Kim et al., 2017) because the starting altitude of retrieval (r_N =36 km) is consistent with the calibration region (36–39 km) for the CALIPSO Level 1B Version 4 product (Kar et al., 2018); therefore, $\Delta C_N\,(r_N)$ is set to 0. The standard deviation of the TAB is used to approximate $\Delta\beta'(0,r)$ because the TAB in this study was pre-processed.

Uncertainty is found in the calibration factor in $\Delta\beta'(0,r)$, which contains systematic and random components (Young et al., 2013), and this approximation neglects the systematic error in the calibration factor, producing a low bias in the uncertainty calculation. Fortunately, the calibration factor bias of the nighttime CALIPSO V4 product has been reduced to 1.6%$\pm$2.4% (Kar et al., 2018). Additionally, Kim et al. (2017) pointed out that the bias caused by the lidar ratio is dominated in the retrieval. Thus, we consider ignoring the calibration factor in the systematic error. The other terms in Eq. (6), total backscatter coefficient ($\beta_T(r)$), molecular and particle two-way transmittance uncertainty ($\Delta T_M^2(r_N,r)$ and $\Delta T_P^2(r_N,r)$), and molecular backscatter uncertainty ($\Delta\beta_M(r)$) are calculated in the same way as in Young et al. (2013) and are not repeated here. S_p and ΔS_p in Eq. (7) are selected from the median and median absolute deviation, respectively, in the retrieved 20°×20° grid lidar ratio based on CALIPSO profile locations.

Also, we discuss the uncertainties corresponding to the different magnitudes of extinction in the retrieval in Section 3.2, as follows:

The nighttime CALIPSO undetected aerosol extinction and SAGE III/ISS 521 nm aerosol extinction show good agreement for the 12-month validation dataset (Figure 5a), with the average retrieved aerosol extinction (black line) closing to the 1:1 line. The correlation coefficients (R) and normalized root mean square error (NRMSE) are 0.66 and 100.6% based on the independent 12-month SAGE validation dataset, respectively….

…The averaged black line in Figure 5b show the mean relative uncertainties of CALIPSO, specifically ~35% and ~125% for the retrieved extinction of 10^{-3} and 10^{-4} km^{-1}, respectively.

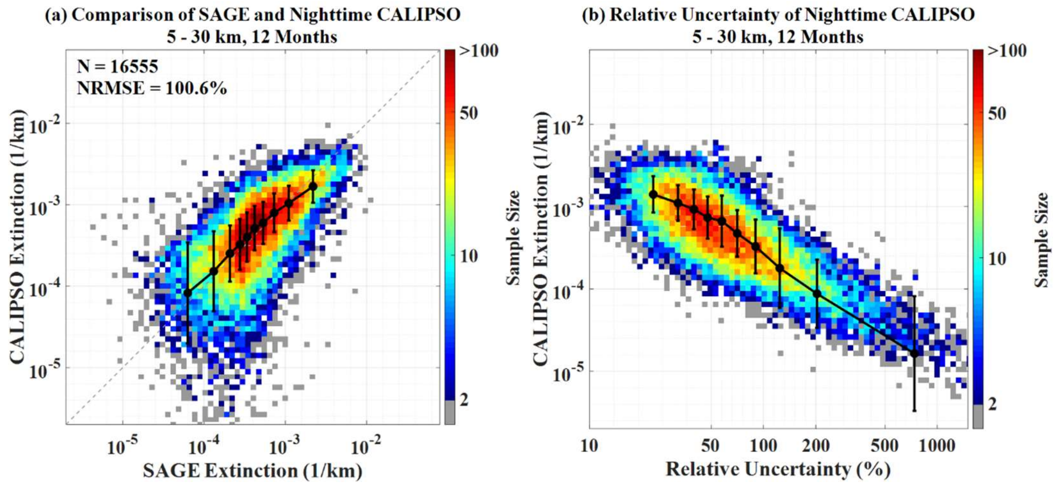

Figure 5. (a) Correlation plots of the retrieval within the matching grid of CALIPSO nighttime and SAGE III/ISS product from 5 km to 30 km for 12 months of validation. The color bar represents the sample size. The black bins represent the mean values of each 10% quantile (0-10%, 10-20%...and 90-100%) of SAGE III/ISS 521 nm aerosol product and corresponding CALIPSO retrieval. The I-type bars indicate the standard error of each 10% quantile CALIPSO retrieval. (b) The relative uncertainty of one-degree CALIPSO extinction.

Specific comments

1. Lines 69-70: "The CALIPSO lidar is highly sensitive to cloud/aerosol layers with a lower bound of optical depth…". What is the lidar highly sensitive to? Presumably layer detection is meant, but the sentence does not say.

   Response: Thanks for your suggestion. This paragraph has been reorganized and this sentence has been deleted.

2. Line 70: "minimum detected extinction of 0.01 to 0.02 /km." This statement does not accurately represent the order of the level 2 CALIOP algorithms. The level 2 algorithms do not detect extinction. Layers are first detected using attenuated scattering ratios and then extinction is retrieved. Suggest rewording to clarify.

   Response: Thanks for your suggestion. This paragraph has been reorganized and this sentence has been deleted. And the similar expressions of "detected extinction" elsewhere in the manuscript have been revised.

3. Line 93-94: Rather than just reference the Kar et al., 2019 paper to explain how clouds and aerosols are removed, it is recommended to add a sentence or two summarizing the removal procedure of that paper. Also, Kar et al., 2019 applies additional filters to remove undetected cloud layers beyond just using the VFM to

cloud-clear. Does the method for this manuscript do the same?

Response: Thanks for your suggestion. We have added an operation for residual cirrus cloud removal, which is illustrated in Section 2.1 now:

(2) The clouds and aerosol layer detected by the SIBYL and the data below them were removed. We used a threshold value of 0.5 in the attenuated color ratio (the ratio of the TAB at 1064 and 532 nm) to remove undetected tenuous cirrus clouds, similar to the data screening method of the CALIPSO Level 3 Stratospheric Aerosol Profile product (Kar et al., 2019).

4. Line 95: "The TAB is averaged at a vertical resolution of 300 m…" How is it possible to average the TAB to 300 m vertical resolution from 20.2 to 30.1 km when the range bins reported in the level 1 data product are at 180 m vertical resolution for that altitude region? Averaging two bins together in this region would yield 360 m, not 300 m. Furthermore, the TAB is already reported at 300 m vertical resolution from 30.1 – 40 km, so no average is required. Please clarify if the averaging used for this study considers the vertical resolution of the range bins in the level 1 data products.

   Response: Sorry for the confusion. In the revised manuscript, we have added a description of the vertical resolution of the CALIPSO Level 1 data and explained that we reducing the vertical resolution to 300 m by linear interpolation in Section 2.1:

   (3) The vertical resolution of the CALIPSO Level 1B TAB profiles varies with the height of 30, 60, 120, and 300 m for −0.5–8, 8–20.2, 20.2–30.1, and 30.1–40 km, respectively. Referring to Kim et al. (2017), the TAB profiles are reduced to a vertical resolution of 300 m by linear interpolation to improve the SNR, followed by a vertical moving mean filtering (with a 5-point window) and horizontal averaging to 20 km to retrieve the extinction of undetected aerosol.

5. Line 147. According to this line, the extinction retrieval yields a value of 0.01 /km. However, the text suggests the layer is smoke, so the lidar ratio being used is too low by 50/70. Therefore, this extinction value should be larger.

   Response: Yes, this bias does still exist in the study and therefore in the revised manuscript we discuss this issue in Section 3.4:

   Figure 7b illustrates a possibly missed smoke from a wildfire. Based on the SAGE-constrained lidar ratio (median 42.2 and 24.5 sr), we retrieved and see the undetected aerosol by CALIPSO Level 2 products, which connects with two strong aerosol layers. The lidar ratio for the smoke in the CALIPSO Level 2 Version 4 product is 70±16 sr (Young et al., 2018), which is very different from the SAGE-constrained lidar ratio for the troposphere at this location. Theoretically, a larger lidar ratio will derive a larger extinction in the retrieval. This indicates that the undetected aerosol extinction should be larger if using the smoke lidar ratio of 70±16 sr. However, this bias cannot be avoided here because an automatic classification is impossible when we do not know the boundaries of those smoke aerosols. Therefore, we have to treat the stratospheric (or tropospheric) undetected aerosols as a whole and assign the same lidar ratio regardless of the aerosol type in this study. Although the retrieved extinction in Figure 7 is biased, it demonstrated the importance of retrieving high spatial-temporal resolution undetected aerosol extinction. A solution to reduce this bias is to develop a more effective layer detection and classification algorithm, and our team is already working on it (Mao et al., 2021).

6. Figure 3. According to pre-processing step (a), clouds and aerosols detected by CALIPSO are removed, along with the data beneath them. However, the purple boundaries in Fig. 3(c) shows that a smoke layer is detected and there is an extinction coefficient reported there. The text even quotes the extinction value on line 148 and panel (d) shows where these layers are detected. I thought that the backscatter was supposed to be removed where layers are reported. Why are they shown in this figure? They are not shown in Figure 7. This should be made clear somewhere which data is used in the retrieval shown in the extinction figure.

Response: Sorry for the confusion, In the revised manuscript we have redrawn this figure as follows:

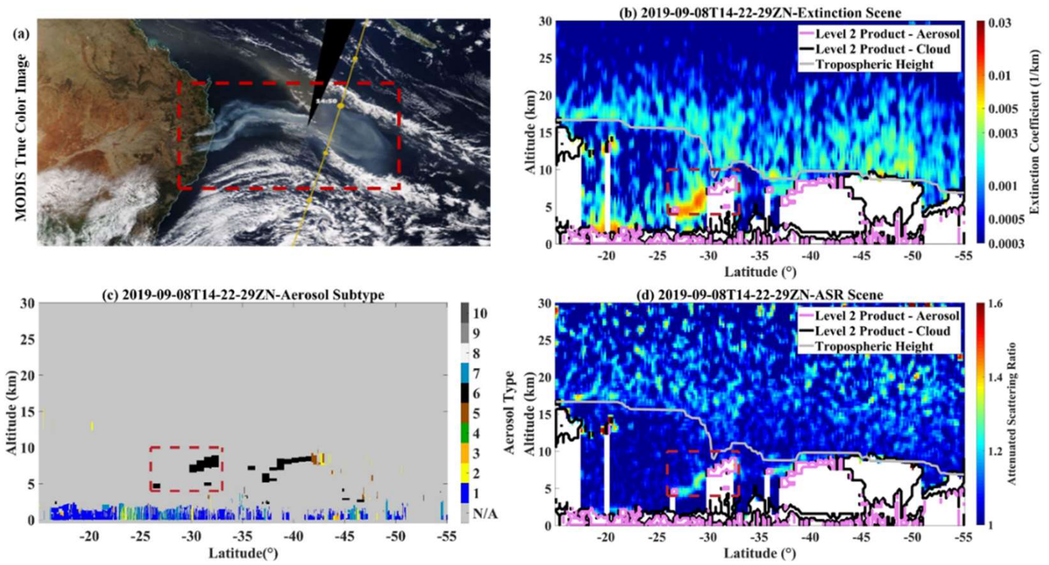

Figure 7. (a) MODIS Terra true-color image in the daytime and the passing CALIPSO track (yellow line) at night. (b) Latitude–altitude aerosol extinction of the corresponding nighttime CALIPSO track, same as in Figure 4a. The purple and black boundary lines and extinction inside represent the detected aerosol and cloud layers provided by CALIPSO Level 2 products, respectively. (c) Aerosol subtypes in CALIPSO VFM product (N/A=not applicable, 1=marine, 2=dust, 3=polluted continental/smoke, 4=clean continental, 5=polluted dust, 6=elevated smoke, 7=dusty marine, 8=PSC aerosol, 9=volcanic ash, 10=sulfate/other). (d) Attenuated scattering ratio.

7. Figure 3 caption. "…additional mean filtering (3x3 window) to highlight the faint aerosol area." The premise of the paper is that averaging to 20 km x 300 m resolution is enough to highlight the faint aerosol. Why is additional averaging needed? Can these features still be discerned without this additional filtering? If not, then should the 3x3 window filtering be included as part of the methodology?.

   Response: Sorry for the confusion. The simple 3×3 mean filtering was used in the mapping of the figure just for visual convenience.

8. Line 173: "…indicating a low bias in the CALIPSO retrieval." Some clarification should be added here because there could be two interpretations of this statement. (1) Because the CALIPSO level 2 layer detection did not capture these extinction values, there is a low bias in what CALIPSO reports. Or, (2) the retrieval of extinction from the CALIPSO products performed in this study has a low bias. Please clarify which condition this statement is addressing.

   Response: We are very sorry for the confusion here. The related sentences have been rewritten as follows:

   The nighttime CALIPSO undetected aerosol extinction and SAGE III/ISS 521 nm aerosol extinction show good agreement for the 12-month validation dataset (Figure 5a), with the average retrieved aerosol extinction (black line) closing to the 1:1 line. The correlation coefficients (R) and normalized root mean square error (NRMSE) are 0.66 and 100.6% based on the independent 12-month SAGE validation dataset, respectively.

9. Line 176: "…we can see that the retrieved aerosol extinction is much less than the detection limit (0.01 km^{-1}) of the CALIPSO Level 2 product". More precise language is requested here. The CALIPSO level 2 algorithms do not detect extinction, they detect layers and then retrieve extinction. This study addresses the extinction from aerosol layers below the layer detection limit of the level 2 feature

finder.

Response: Modified, as follows:

This indicates the retrieved extinction of undetected aerosol is much smaller than the low boundary of the detected aerosol extinction (10^{-2} km^{-1}) from the CALIPSO Level 2 extinction product with a 40% uncertainty (Kacenelenbogen et al., 2011; Toth et al., 2018; Winker et al., 2013; Winker et al., 2009).

10. Lines 198 – 200: “Young et al. (2013) noted that the CALIPSO retrievals with SNR≤1 usually contain a positive bias. The SNR during daytime above 20 km is usually less than 1 for TAB at 20 km horizontal scale (Figure 6b), which leads to a significantly positive bias in the retrieval” It is not immediately clear how an SNR < 1 yields a positive bias. SNR speaks toward the (inverse of the) variability with respect to the average value, but not necessarily a bias. I would assume that a bias is more governed by calibration rather than noise. Or is it that the noise is not Gaussian? Please add information as to why a “significantly positive bias” is expected in the retrieval when SNR < 1.

    Response: Additional explanations have been given in the manuscript as to why positive bias occurs when the SNR < 1, as follows:

    The distribution of lidar signals received by photomultipliers is Neyman type-A (originally defined for a Poisson process) (Teich, 1981), thereby introducing a positive bias in the extinction retrieval calculation when the SNR is low. Also, Young et al. (2013) noted that the CALIPSO retrievals with SNR≤1 usually contain a positive bias. The SNR during daytime above 20 km is usually less than 1 for TAB at a 20 km horizontal scale (Figure 6b), leading to a significantly positive bias in the retrieval (Figure 6a), as noted by Young et al. (2013).

11. Line 210: It would be helpful to explain why the white areas of missing data occur between ± 15° in the level 3 panels of Figure 7 (because of the tropopause height).

    Response: The missing data between ± 15° in the original manuscript is due to the higher tropospheric height at lower latitudes. In the revised manuscript, the height of the CALIPSO Level 3 product has been changed to 17 km to correspond to the aerosol enhanced area in the retrieved extinction scene map:

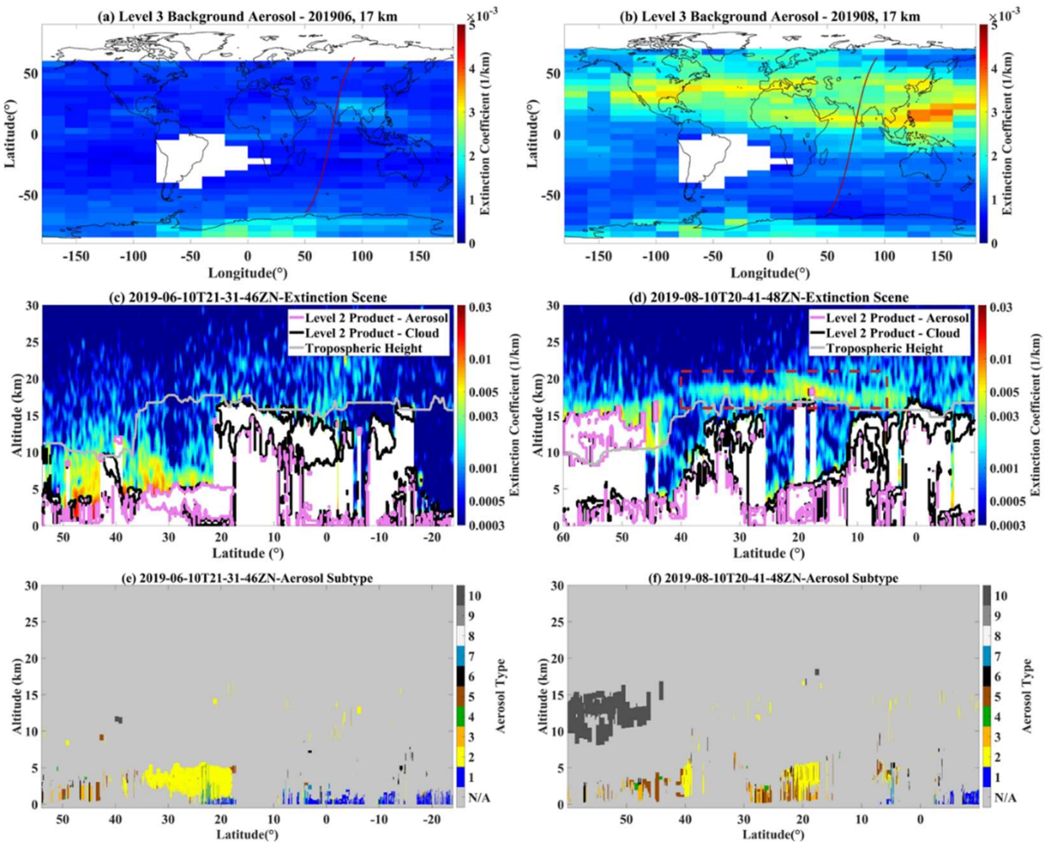

Figure 8. (a) and (b) are the stratospheric extinction distributions of CALIPSO Level 3 Stratospheric Aerosol Profile products at 17 km in June and August, respectively. (c) and (d) are the retrieved aerosol extinction scenes based on CALIPSO instantaneous data on June 10 and August 10, respectively, consistent with Figure 4a. The corresponding trajectories for the two scenes are shown as red lines in (a) and (b), and the corresponding aerosol subtypes are shown in (e) and (f), the same as in Figure 7c.

12. Section 3.3. Possible smoke from Siberian wildfires is not the only explanation for aerosol enhancement in the stratosphere during this time period. The June 2019 Raikoke volcano eruption also emitted a substantial amount of sulfate at northern latitudes. This should be discussed as part of the explanation and interpretation for aerosol enhancement in August 2019.

Response: Sorry for the confusion. We check the aerosol distribution at tropopause and stratosphere during the summer of 2019 based on CALIPSO L3 monthly-average data. The aerosol enhancements in August of 2019 are consistent with Raikoke volcanic eruption, as shown in Figure 8. Further, we compare aerosol at 17 km in August of 2018 and 2019 (Figure R1) to confirm these aerosol enhancements are unique in 2019. The Raikoke volcanic eruption has been added to the interpretation of stratospheric aerosol enhancement in the Northern

Hemisphere in August 2019 (Knepp et al., 2021; Kloss et al., 2021), as follows:

A significant amount of aerosol enhancement was observed in the stratosphere in August in the northern hemisphere (Figure 8b), possibly due to the eruption of the Raikoke Volcano in June 2019 (Knepp et al., 2021; Kloss et al., 2021).

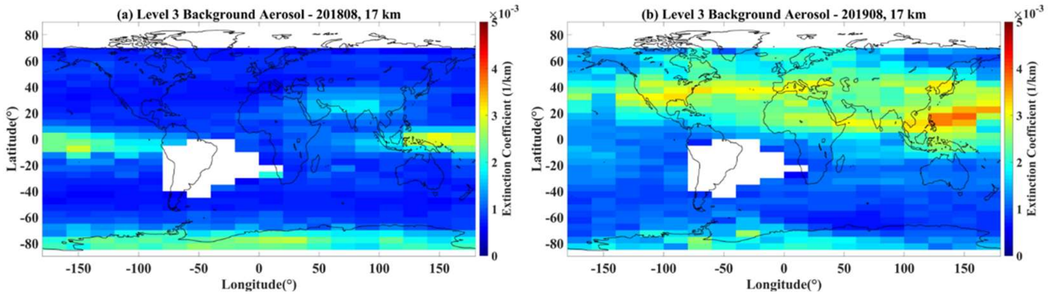

Figure R1 (a) and (b) are the stratospheric extinction distributions of CALIPSO Level 3 Stratospheric Aerosol Profile products at 17 km in August 2018 and August 2019, respectively.

13. Line 225: "These faint aerosols propagate from 60N to near 10N…" The word "propagate" might be inaccurate for this discussion.

    Response: Thanks for your suggestion, we have removed the expression about "propagate", as follows:

    Following the onset of volcanic eruptions, strong stratospheric aerosol layers are found in the stratosphere between 50°N and 60°N that are classified as sulfate by the VFM (Figure 8f). As shown in the red dash box of Figure 8d, aerosol extinction enhancement (~0.005 km^{-1}) occurs around 17 km near 40°N to 5°N, which corresponds to the monthly average scale aerosol contamination in the stratosphere throughout the Northern Hemisphere in Figure 8b, but is not captured by CALIPSO Level 2 products (Figure 8f).

14. Lines 243 – 244: "The retrievable aerosol extinction greatly extends to 0.0001 km-1…" What is the relative error on these very low extinction values?

    Response: A discussion of the relative uncertainty in the retrieved extinction has been added to the revised manuscript, as described in the response of Major Comment 3 and in the following:

    The averaged black line in Figure 5b show the mean relative uncertainties of CALIPSO, specifically ~35% and ~125% for the retrieved extinction of 10^{-3} and 10^{-4} km^{-1}, respectively.

15. Lines 244 – 246: “The comparison is unavailable at low altitudes, but the retrieval should be more reliable (i.e., in the troposphere) because the SNR is higher.” The improvement in SNR is only part of the story. A far more substantial factor that will cause larger errors in the troposphere is the choice of lidar ratio, which can range from 20 – 70 sr. This can cause the biases up to a factor of three when the wrong lidar ratio is used. It is important to include a discussion on how the choice of lidar ratios for this analysis impacts comparisons with SAGE retrievals.

    Response: You are right. We have removed the comparison on SNR of SAGE III/ISS and CALIPSO and added the discussion of the effect of lidar ratio selection on retrieved extinction, as described in the response of Major Comment 2.

16. Lines 247 – 248. Same question as before, how does low SNR yield a positive bias? More should be added here to summarize why this is true.

    Response: Additional explanations have been given in the manuscript as to why positive bias occurs when the SNR < 1, as follows:

    The distribution of lidar signals received by photomultipliers is Neyman type-A (originally defined for a Poisson process) (Teich, 1981), thereby introducing a positive bias in the extinction retrieval calculation when the SNR is low. Also, Young et al. (2013) noted that the CALIPSO retrievals with SNR≤1 usually contain a positive bias. The SNR during daytime above 20 km is usually less than 1 for TAB at a 20 km horizontal scale (Figure 6b), leading to a significantly positive bias in the retrieval (Figure 6a), as noted by Young et al. (2013).

17. Lines 249 – 252. A couple of points about conclusion item (3).

    First, the stratospheric aerosol enhancement for this time period includes contributions from the Raikoke volcanic plume in addition to (possible) smoke from Siberian wildfires. This should be included with the discussion of sources for this example. There is some discussion in the literature about the contribution of these aerosol types in August 2019.

    Second, this sentence can easily be interpreted as an over-generalization, “our retrieval shows that these faint aerosols even propagate to near 10°N, which is much beyond the detecting range of the CALIPSO L2 products (50° N and 60° N).” I believe this sentence is a summary of the single level 2 granule evaluated in Figure 7 where the level 2 algorithms did not detect a large extent of the stratospheric aerosol enhancement from 10N to 50N, Fig 7(d). For this specific case, the aerosol was not detected by CALIOP level 2. However, the sentence is written as though this is a general result: faint aerosols following the 2019 Siberian fires (and

Raikoke eruption) are not detected as far south as 10N by CALIOP level 2 retrievals. This cannot be concluded based on the one granule examined. To make the possibility of misinterpretation more probable, Figure 7(b) shows nothing reported in the CALIOP level 3 stratospheric aerosol product from about 15 N/S. This is merely because the tropopause is above 15.2 km at those latitudes, but a reader could easily read this sentence and look at Figure 7(b) and conclude that CALIOP level 2 missed detecting all of that aerosol during August 2019. It is unlikely that CALIOP level 2 did not detect all of this aerosol, and even if so, it was not proven in the manuscript. I recommend rephrasing conclusion item (3) to be more specific on the evidence for the conclusion being made.

Response: Thank you for your comment. Based on the new methods, results and discussions, we rewrote the conclusions as follows:

(1) The lidar ratio for the stratosphere and troposphere in global is derived based on CALIPSO instantaneous observations using SAGE III/ISS AOD as a constraint. The derived lidar ratio is significantly higher in the stratosphere (median 42.2 sr) than that in the troposphere (median 24.5 sr). The derived lidar ratio peak at the equator and decrease with latitude at the stratosphere, while the lidar ratio variations are small at the troposphere in global.

(2) The retrieved undetected aerosol extinction based on CALIPSO nighttime instantaneous observations shows good agreement with the SAGE III/ISS product on a 1° average. The correlation (*R*) and NRMSE are 0.66 and 100.6% based on the independent 12-months SAGE III/ISS data, respectively. The uncertainties of retrieved extinction coefficients at 10^{-3} km^{-1} and 10^{-4} km^{-1} are ~35% and 125% during nighttime, respectively.

(3) The comparison of retrieved undetected aerosol extinction based on globally fixed and SAGE-constrained lidar ratios indicates the NRMSE decreased by about 15% (from 120.2% to 105.6%) during nighttime. Additionally, the CALIPSO retrieval during daytime has a positive bias and relatively low agreement with SAGE III/ISS; it exhibits R and NRMSE of 0.25 and 454.5%, respectively, due to the low signal-to-noise ratio caused by sunlight.

(4) In the case of the Australian wildfire event, instantaneous retrieved extinction of missed aerosol from CALIPSO Level 2 products provides more details of aerosol distribution. In addition, compared with the CALIPSO Level 3 stratospheric aerosol product, the retrievals show consistent aerosol enhancement possibly due to the eruption of Raikoke Volcano, but at a higher spatial-temporal resolution.

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