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Original title: CALIPSO Retrieval of Instantaneous Faint Aerosol

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

General comment

The space-borne lidar CALIOP on board CALIPSO satellite has been providing global measurements of aerosol and cloud backscatter profiles since 2006. Successive improvements in algorithms and calibration procedures have resulted in several versions of the products. Nonetheless there is always scope for further improvements. In particular, it has been known that aerosols with weak backscatter sometimes fall below the CALIOP layer detection threshold and several works have focused on this aspect as has been pointed out by the authors.

In this paper the authors attempt to retrieve what they call "instantaneous faint" aerosols using the CALIOP backscatter data in both the stratosphere and troposphere and compare the results with SAGE III on ISS. Firstly it is not clear to me what the authors mean by "faint" aerosols---are these background aerosols or aerosols that just fall below the detection threshold but otherwise retain the intensive optical properties of the nearby detected layers. The methodology is nothing new and Kim et al. (2017) have used the same 20 km horizontal and 300 m vertical averaging for their extinction retrievals. The Kim et al. (2017) paper did a much more comprehensive study of the weak aerosols unlike this manuscript which lacks in some important details and other aspects, as described below. I do not believe this paper presents enough innovative ideas or interesting new results that will be useful to the community. I regret that I am not able to recommend this manuscript for publication in Atmospheric Chemistry and Physics. I have the following comments in no particular order:

Response: Thank you for your careful review. We have made great efforts to address the issues you raised and highlight our significance, 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 (Section 2.4). This study no longer uses the fixed lidar ratio (i.e. 28.75 sr) as used in Kim et al. (2017). We add the 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.

(3) Uncertainties in the extinction coefficient retrieval were calculated to assess the reliability of the extinction results of undetected aerosol.

(4) The Raikoke eruption event is added to the comparison of 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.

Major comments

1. The authors seem to use a constant altitude bin of 300 m to average the level 1 (L1) backscatter profiles in the entire altitude range from 0-36 km. This is not tenable, because CALIPSO L1 backscatter profiles have varying resolution with altitude, with 30 m from surface to 8.3 km, 60 m between 8.3-20.2 km, 180 m between 20.2-30.1 km and 300 m above 30.1 km. Properly accounting for these differences will require setting the binning at 900 m as was done in Kar et al. (2019) for the level 3 stratosphere aerosol product.

   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.

2. I am surprised that the authors are talking about the "instantaneous faint" aerosols in the extinction range 10^{-4}-10^{-5} km^{-1} and yet do not mention the estimated uncertainties for these extinction profiles at all. When they are claiming to do better than the standard CALIPSO level 2 (L2) and level 3 (L3) products, they should discuss the resulting uncertainties for their extinctions to bolster their claims. Kim et al. (2017) had discussed in detail the uncertainties in their retrievals particularly those coming from the lidar ratios used. The lack of any such discussion in this paper is a major drawback.

   Response: 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 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.

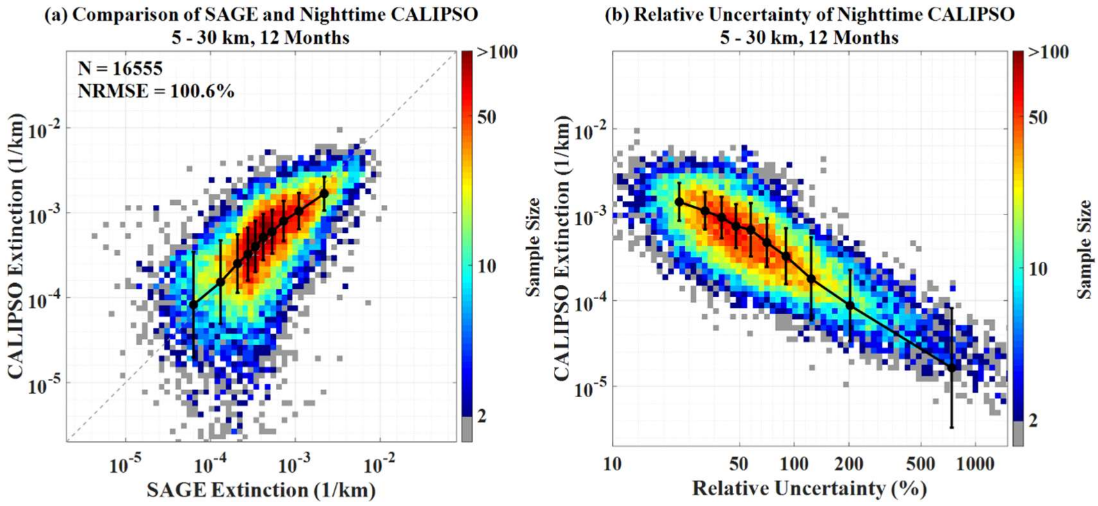

Figure 5. (a) Correlation plots of the retrieval within the matching grid of CALIPSO nighttime and SAGE III/ISS product from 5 km to 30 km for 12 months of validation. The color bar represents the sample size. The black bins represent the mean values of each 10% quantile (0-10%, 10-20%...and 90-100%) 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.

3. In their retrieval algorithm they mention excluding the aerosol and cloud layers detected by the CALIOP L2 algorithm and all data below those layers similar to the methodology employed in Kar et al. (2019). However one important filter has been left out which has to do with the thin cirrus clouds. These clouds often fall below the layer detection threshold and can significantly contaminate the "faint" aerosol profiles they are trying to retrieve particularly in the UTLS area. Kar et al. (2019) had used a filter on the volume depolarization ratio to take out these ice clouds. In fact cloud clearance can be an issue with SAGE occultation measurements as well, which affect the data below 20 km (Thomason and Vernier, 2013, https://doi.org/10.5194/acp-13-4605-2013). It is not clear if the authors have used any filter for cloud-clearing of SAGE III data. Further note that the SAGE III-ISS 521 nm extinction product has low bias between 20 km and 25 km at mid latitudes possibly relating to the ozone interference (Knepp et al., 2022, https://doi.org/10.5194/amt-2021-333). These issues should have repercussions for the CALIPSO/SAGE III comparisons the authors have attempted.

Response: Good suggestions! We have added the removal of thin cirrus clouds of CALIPSO data in Section 2.1, as follows:

(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).

The cloud-contaminated data in SAGE III/ISS was removed in Section 2.2, as follows:

We removed the bins in the SAGE III/ISS aerosol extinction profile with color ratio (the ratio of the aerosol extinction at 521 and 1022 nm) in the range of 0.8 to 1.2 to avoid cloud contamination (Schoeberl et al., 2021).

The SAGE III/ISS 521 nm aerosol extinction product was corrected with reference to Knepp et al. (2021).

A low bias in the extinction coefficients of the SAGE III/ISS aerosol product is observed at 521 nm due to the ozone interference in the retrieval algorithm. This finding is more pronounced at mid-latitudes and altitudes between 20 and 25 km (Knepp et al., 2021). The following equation is therefore used to correct the extinction at 521 nm (Knepp et al., 2021):

$$log\,\sigma_{521} = \frac{log\,(\frac{\sigma_{450}}{\sigma_{755}}) \times log\,(\frac{521}{755})}{log\,(\frac{450}{755})} + log\,(\sigma_{755}), \tag{1}$$

where σ is the extinction coefficient, and the numbers represent the wavelength.

4. The authors use a lidar ratio of 50 sr in the stratosphere and 28.75 sr in the troposphere. In Figure 3, they are retrieving “faint” aerosol in between and in continuity with the smoke layers retrieved by CALIOP L2 product, assuming that the “faint” aerosol is also smoke and referring to “the continuous nature of this aerosol layer”. For smoke, CALIOP L2 uses a lidar ratio of 70 sr, so the “faint” aerosol extinctions retrieved using a lidar ratio of 28.75 sr will have a significantly low bias. I am also intrigued by the distinct band of “faint” aerosols above 10 km extending from 15°S-55°S—is this background aerosol, smoke? Indeed how confident are the authors that it is aerosol at all? Similarly in the ASR plot Figure 3e, what are all those clumps between 10-30 km? It all just looks like noise to me although the ASR values are quite significant (~1.3) and about the same as within the pink box. Similarly in Figure 7, the authors are showing the plume of “faint” aerosols “connected with the VFM aerosol features”—i.e Siberian smoke extending from 10oN-60oN. Once again, they should use the more appropriate lidar ratio for smoke (70 sr) rather than that (50 sr) for stratospheric background aerosols. Since the authors use coincident extinction data from SAGE III-ISS, have they tried to obtain the lidar ratio (in Figure 4b, for instance) using the extinction

from SAGE III and backscatter from CALIOP following the method given in Kar et al. (2019)? It will be interesting to see how those compare with the values they are using.

Response: You are right, the lidar ratio selection is one of the keys in retrieval. We have improved the lidar ratio selection using SAGE III/ISS AOD as a constraint as described in section 2.4.

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.

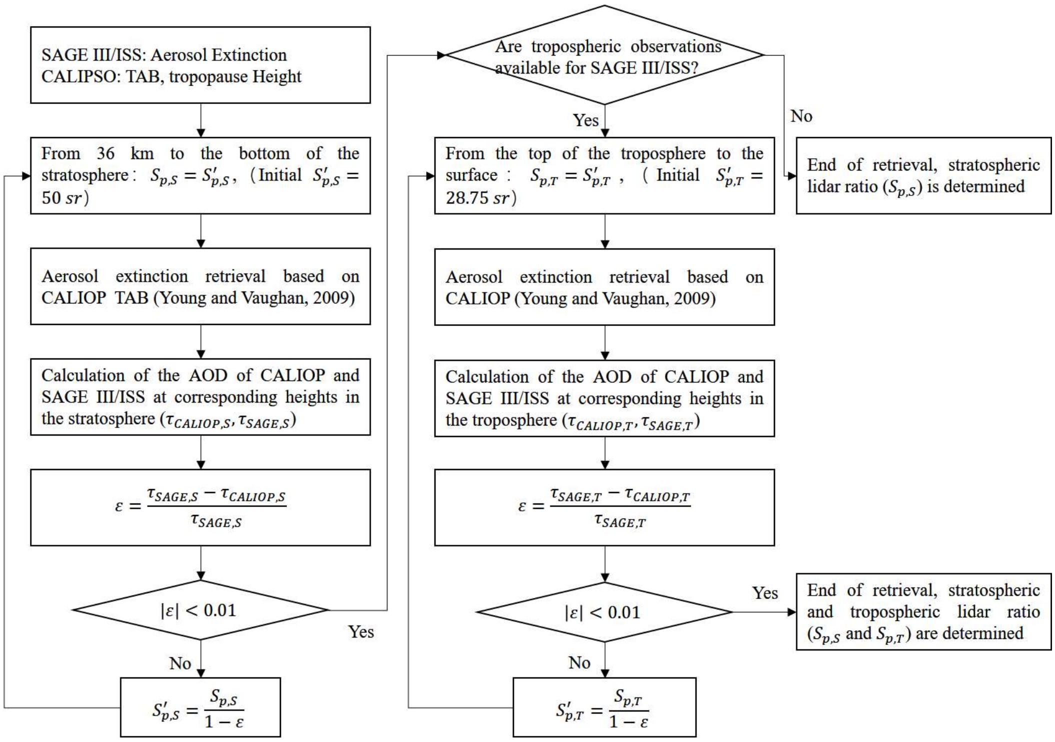

Figure 2. Flowchart for the retrieval of lidar ratio by using SAGE III/ISS AOD as a constraint .

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.

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.

The global distribution of the SAGE-constrained lidar ratios is presented in section 3.1, as follows.

3.1 Global gridded distribution of lidar ratio

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)).

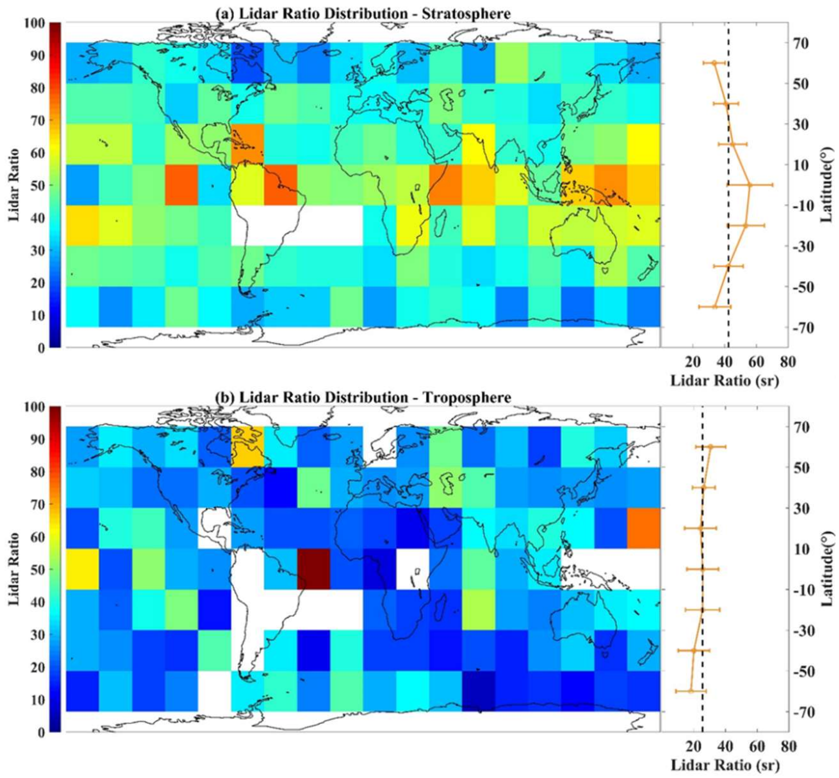

Figure 3. (a) (a) Global stratospheric distribution of lidar ratios with a grid size of 20° x 20°. The color bar represents the lidar ratio value. The line on the right shows the median variation at 20° intervals from −70° to 70° (latitude) globally, and the error bar represents the median absolute deviation.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

We have therefore added a section (Section 3.4) to discuss the effect of the lidar ratio

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.

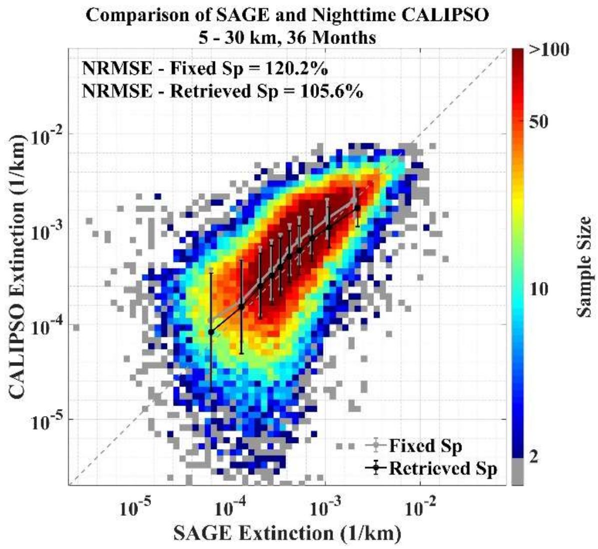

Figure 9 The colored scatter plot is the same as that in Figure 5a, but the CALIPSO extinction are retrieved using fixed lidar ratios of 50 and 28.75 sr in stratosphere and troposphere from June 2017 to May 2020, respectively. The gray and black lines are the mean value of of each 10% quantile (as in 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).

In addition, we have added the calculation of the extinction uncertainty for the retrieval to indicate how confidently the retrieval is true for the undetected aerosol in Section 2.4. Also, we discuss the uncertainties corresponding to the different magnitudes of extinction in the retrieval in Section 3.2, as described in Comment 2.

5. It seems to me that in Figure 4, the layer at ~15 km is detected and retrieved by standard CALIOP L2---wonder how that compares with the profiles the authors retrieve. In any case the "faint' layers between 15-20 km in this Figure do not look quite faint to me, and is likely the aerosol that just missed the layering threshold of standard L2.

   Response: Sorry for the confusion, in this study, faint aerosol refers to the aerosol undetected by CALIPSO Layer Detection Algorithm. We now clarify the definition of weak aerosols and give it directly in the revised title.

   Retrieving Instantaneous Extinction of Aerosol Undetected by CALIPSO Layer Detection Algorithm

6. As the authors have mentioned, CALIOP has been experiencing low energy laser shots since late 2016 primarily impacting the SAA region and accordingly they have excluded the SAA region. However those low energy shots have been spreading to other latitudes as well and can lead to artifacts in the data including false layer detections at all altitudes, particularly in the dayside. These effects can impact the extinction retrievals the authors are attempting and can be alleviated using the prescription given in the data advisory.

   Response: Thank you for your suggestion, we have removed the affected CALIPSO data according to the data advisory, as follows:

   (1) We removed the affected CALIPSO observations according to Low Laser Energy Technical Advisory due to the effects of an elevated frequency of low-energy laser shots of CALIPSO within the South Atlantic Anomaly (SAA) (https://www-calipso.larc.nasa.gov/resources/calipso_users_guide/advisory).

7. Line 173-174—"Further, 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" and lines 234-235—"Instantaneous retrieval of faint aerosol at 20 km horizontal resolution provides a chance to deeper understand and quantify the aerosol impact on climate beyond the current CALIPSO Level 3 Stratospheric Aerosol Profile product". I think the authors are missing the rationale behind the L2 and L3

products. In my understanding CALIOP L2 first detects a ”layer” using a range-dependent threshold and then assigns an aerosol subtype to it, for which a lidar ratio is available. This lidar ratio varies from 23-70 sr. The layer detection scheme for relatively low SNR measurements like CALIOP is quite complicated (Vaughan et al., 2009, doi:10.1175/2009JTECHA1228.1) and was designed to minimize false positive detections which leads to some undesired missed detections. However, overall it has worked very well and without this and (hopefully) proper assignment of lidar ratios for those different types of aerosols, CALIOP products would not be as useful as they have been. The next generation detection scheme for lidars uses 2D algorithms using both 532 nm and 1064 nm backscatter measurements and will lead to much more accurate detections including those of weakly scattering particulates (see Vaillant de Guelis et al., 2021, https://doi.org/10.5194/amt-14-1593-2021). On the other hand, in the L3 stratospheric aerosol product, which is built from the L1 profiles, the retrieved extinctions are of the same order as the authors retrieve here. The L3 product has low spatial resolution (5^{o}x20^{o} in lat/lon necessary to increase the SNR and produces a reliable picture of the known stratospheric features) and is geared towards modelling applications. In other words, the L2 and L3 products have different goals and limitations. L2 products in the stratosphere employ different lidar ratios for different subtypes (ash, sulfates, smoke) unlike in the L3 product where a constant value is used for background as well as the full-aerosol mode. If the authors propose to retrieve the “instantaneous faint” aerosols in between the layers of different subtypes (as in Figures 4 and 7) then they should use the appropriate lidar ratios as mentioned above---this entails using the subtypes defined in CALIOP L2 or they can define their own subtypes.

Response: Thank you very much for your suggestions. In the revised manuscript, we have added a description of the scientific process for each level of CALIPSO product to help the reader understand the relationship between our study and the current CALIPSO products (i.e., fill the gap of the high spatial and temporal distribution of undetected aerosols in CALIPSO Level 2 and Level 3 products) in Section 2.1, as follows.

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 a monthly averaged gridded global distribution data of clouds and aerosols (Kar et al., 2019).

At the same time, we reorganize the statements you point out here to maintain a correct understanding of the scientific objectives of the CALIPSO product while comparing retrieved results and them in Section 3.2.

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. 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). Similarly, Watson‐Parris et al. (2018) noted through the model that the minimum value of aerosol extinction at 0–15 km should be close to 10^{-4} km^{-1}, whereas CALIPSO Level 2 aerosol products remain above 10^{-2} km^{-1}, and the mean fraction of aerosol undetected by CALIPSO daytime (nighttime) retrievals is 92% (87%) globally.

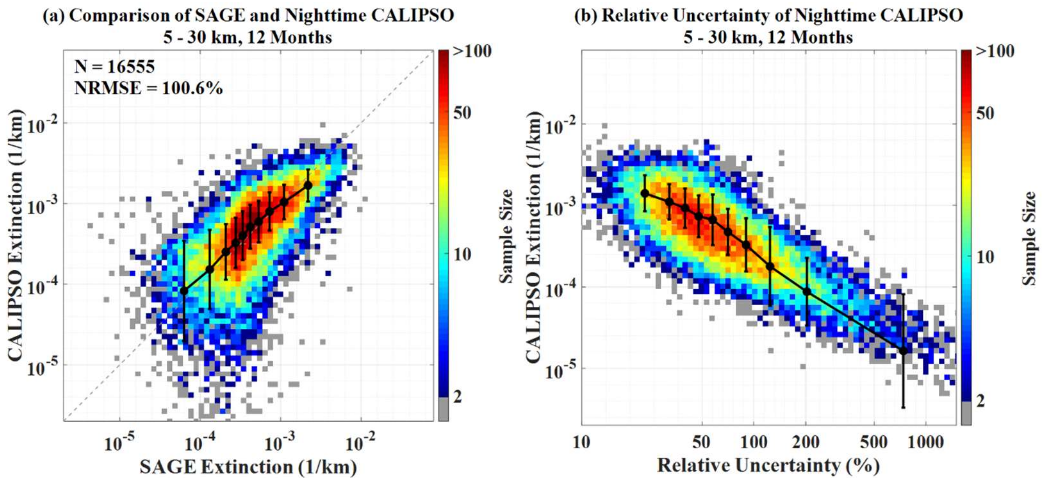

Figure 5. (a) Correlation plots of the retrieval within the matching grid of CALIPSO nighttime and SAGE III/ISS product from 5 km to 30 km for 12 months of validation. The color bar represents the sample size. The black bins represent the mean values of each 10% quantile (0-10%, 10-20%...and 90-100%) 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.

Furthermore, we discussed the limitations of the use of lidar ratios in the current study, as responded to in Comment 4. We are also working on the layer detection and classification algorithm (Mao et al., 2021), which is very potential to improve both the retrieval of the detected and the undetected aerosols in the future.

8. Section 3.3. The authors assume all of the stratospheric perturbation in the northern mid/high latitude is coming from the Siberian wildfires. Much of this may actually be from the Raikoke volcanic eruption (June 2019) instead (Kloss et al., 2021, https://doi.org/10.5194/acp-21-535-2021, Knepp et al., 2022, etc.).

   Response: Thank you for your suggestion. The Raikoke volcanic eruption has been added to the interpretation of stratospheric aerosol enhancement in the Northern Hemisphere in August 2019, 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).

9. Lines 226-229 and lines 250-252. I don't understand how from one browse image the authors can show "faint" aerosol "propagating" from 60oN to 10oN. By the way the CALIPSO transect shown in Figure 7b passes through the well-known Asian Tropopause Aerosol Layer or ATAL (Vernier et al., 2011, https://doi.org/10.1029/2010GL046614, Fairlie et al., 2020, https://doi.org/10.1029/2019JD031506, etc.) region. How do they know it's all smoke from Siberia (or, sulfates from Raikoke) rather than at least partly being contributed by ATAL? In fact the ATAL feature mostly falls below the CALIOP layer detection and is seen in the adequately averaged L1 data as in CALIOP L3 product.

   Response: Sorry for the confusion. The figure and related sentence have been revised. And the Raikoke volcanic eruption has been added to the interpretation of stratospheric aerosol enhancement in the Northern Hemisphere in August 2019.

   Figures 8a and 8b show the spatial distribution of aerosol extinction averaged in June and August 2019 at 17 km altitude from CALIPSO Level 3 monthly-averaged Stratospheric Aerosol Profile product with the resolution of 5°×20° in latitude and longitude (Kar et al., 2019). 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). We selected two CALIPSO tracks across aerosol enhancement areas in June and August (Figures 8c and 8d), respectively. The stratosphere at the northern hemisphere latitudes is clean, whereas natural dust aerosol prevails in the lower troposphere on June 10 when Raikko has not yet erupted (Figures 8c and 8e). The clean condition shown by our retrieval is consistent with the CALIPSO Level 3 products that indicate the clean stratosphere at a monthly temporal scale.

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). Therefore, the retrieved undetected aerosol extinction can well capture the aerosol enhancement from special events at a horizontal resolution of 20 km (Figure 8d). The color ratios, particle depolarization ratios, and integrated attenuated backscatter are extracted manually for the red dashed region (16 km to 20 km, 40°N to 5°N) with an average of 0.17, 0.02 and 0.00033 sr^{-1}, respectively. Using these optical and non-optical properties (i.e., center height, temperature and latitude), aerosol subtypes can be determined by the CALIPSO Scene Classification Algorithms (Kim et al., 2018). The results show that the aerosol subtype in this region is sulfate, which supports that the aerosol enhancement is more likely to be from the eruption of the Raikoke Volcano.

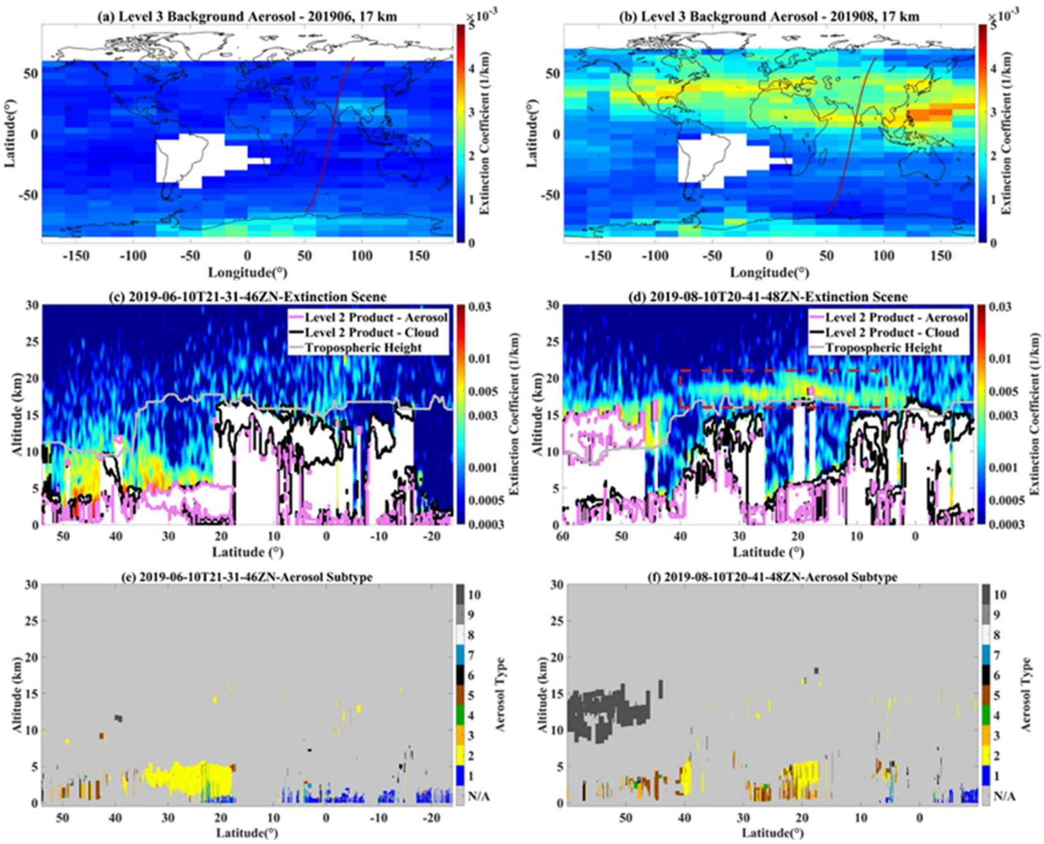

Figure 8. (a) and (b) are the stratospheric extinction distributions of CALIPSO Level 3 Stratospheric Aerosol Profile products at 17 km in June and August,

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.

Additionally, we did not see stratospheric aerosol enhancement in the same regions in 2018 consistent with 2019 (Figure R1) Therefore, we do not think the stratospheric aerosol enhancement in 2019 (Figure 8) is the result of the well-known Asian Tropopause Aerosol Layer.

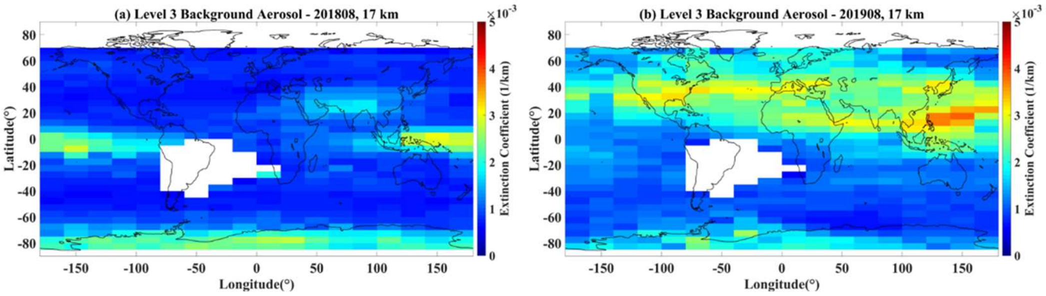

Figure R1 (a) and (b) are the stratospheric extinction distributions of CALIPSO Level 3 Stratospheric Aerosol Profile products at 17 km in August 2018 and August 2019, respectively.

10. Line 84, line 188—The aerosol product discussed in Thomason et al. (2010) paper related to the SAGE III instrument on Meteor 3M spacecraft, not the ISS.

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

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