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

General comment

In this manuscript, the authors use the instantaneous observations of CALIOP to retrieve faint aerosols missed by CALIOP's official aerosol layer and profile products. Comparison analyses with SAGE III aerosol product demonstrate good agreement from the middle troposphere to the stratosphere. Also, in the 2019 Siberian fire event, retrieved instantaneous aerosol provided more information on faint aerosol propagation trajectory with higher spatial and temporal resolution than CALIPSO Level 3 monthly-averaged aerosols product.

This study is very interesting because most of the previous studies focused on aerosol and cloud layer retrieval, but the authors propose a novel method to retrieve the generally-ignored faint background aerosol based on CALIOP instantaneous observations. The manuscript is well-written and straightforward. The results are satisfactory and effectively described. This method is expected to provide new data for the investigation of aerosol-cloud interaction, which may offer new insights into the aerosol climate effect that otherwise cannot be seen by studies based on integrated or surface aerosol information (i.e., AOD). Therefore, I suggest this manuscript be published after minor revisions.

***Response*:** Thank you for your careful review. We have made great efforts to address your comments, and improved this manuscript largely. 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). 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 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 instantaneously retrieved undetected aerosol extinction and Level 3 product in Section 3.3.

Major comments

1. The introduction needs to become more refined and better linked to the scientific literature. It should be clearer where the gaps are in the literature and what the contribution of this study is in this respect.

   Response: The introduction has been revised to highlight the research objectives and significance of this paper. The main changes are as follows.

   (1) The statements in this section have been polished to make the background clear.

   Few studies focus on retrieving aerosols undetected by the CALIPSO detection algorithm (Kar et al., 2019; Kim et al., 2017). Kim et al. (2017) attempted to calculate the missing AOD of these undetected aerosols by constraining of the MODIS AOD over ocean. However, that study mainly focused on the AOD of the undetected aerosol with a fixed lidar ratio, but the extinction of the undetected aerosol was rarely discussed and verified. Additionally, Kim et al. (2017) provided the same lidar ratio (28.75 sr) for the troposphere and stratosphere globally, potentially introducing large uncertainty for extinction retrieval. Recently, the CALIPSO Level 3 Stratospheric Aerosol Profile product was released. However, the purpose of CALIPSO Level 3 products is to provide monthly grid data (5°×20° in latitude and longitude) (Kar et al., 2019), which are insufficient to support studies sensitive to temporal and spatial variations of aerosols, such as studies of aerosol and cloud interactions (Ma et al., 2015). Furthermore, many studies suggest that CALIPSO may potentially obtain more information on faint aerosols with appropriate data processing (Thomason et al., 2007; Vernier et al., 2009; Kar et al., 2019).

   (2) The summary of the research has been rewritten to highlight the innovation and significance of the study, as follows:

   Thus, the present study focuses on retrieving the instantaneous extinction of aerosol undetected by the CALIPSO detection algorithm based on the single-track CALIPSO data. The global distribution of the lidar ratio is obtained with the constraint of the Stratospheric Aerosol and Gas Experiment III on the International Space Station (SAGE III/ISS) observation in the troposphere and stratosphere, respectively. Furthermore, the CALIPSO nighttime and daytime extinction coefficients are retrieved and compared against independent SAGE III/ISS data and CALIPSO Levels 2 and 3 aerosol products. Finally, the impacts of the retrieved lidar ratio and empirical lidar ratio are discussed.

2. The authors use a lidar ratio of 28.75 sr in the troposphere, referring to Kim et al. The lidar ratio is one of the key parameters for aerosol extinction retrieval and varies with aerosol type. Therefore, I suggested the authors more deeply discuss and analyze the lidar ratio, including the difference between land and ocean.

Response: Thanks for your suggestion. In this study, a new method is utilized for lidar ratio retrieval by using SAGE III/ISS AOD as a constraint globally (including over land and ocean). 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 is 0.01 km^{-1} with 40% uncertainty (Kacenelenbogen et al., 2011; Toth et al., 2018; Winker et al., 2013; Winker et al., 2009). The new method is described in Section 2.3, as 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.

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).

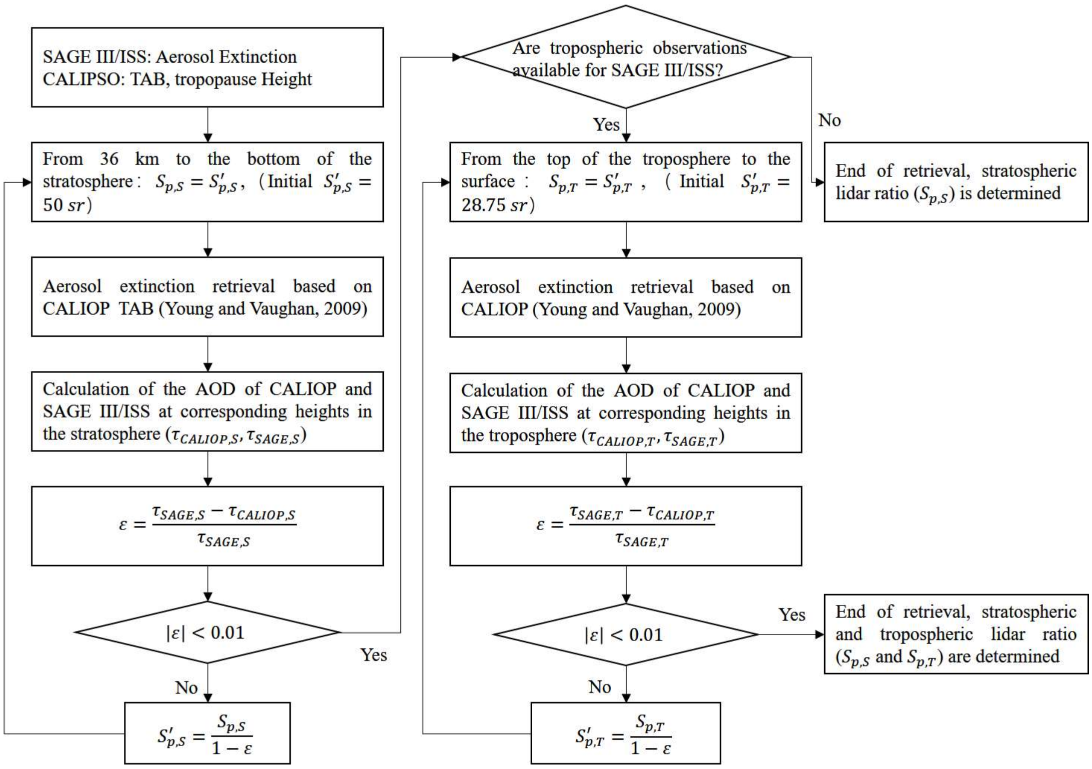

Figure 2. Flowchart for the retrieval of lidar ratio by using SAGE III/ISS AOD as a constraint.

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.

We get the SAGE-constrained lidar ratio at stratosphere and troposphere in global (including over land and ocean), respectively, as shown in Figure 3.

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. In addition, the median absolute deviation of the lidar ratio in the grid is used to calculate the uncertainty of the extinction (Eq. (7)).

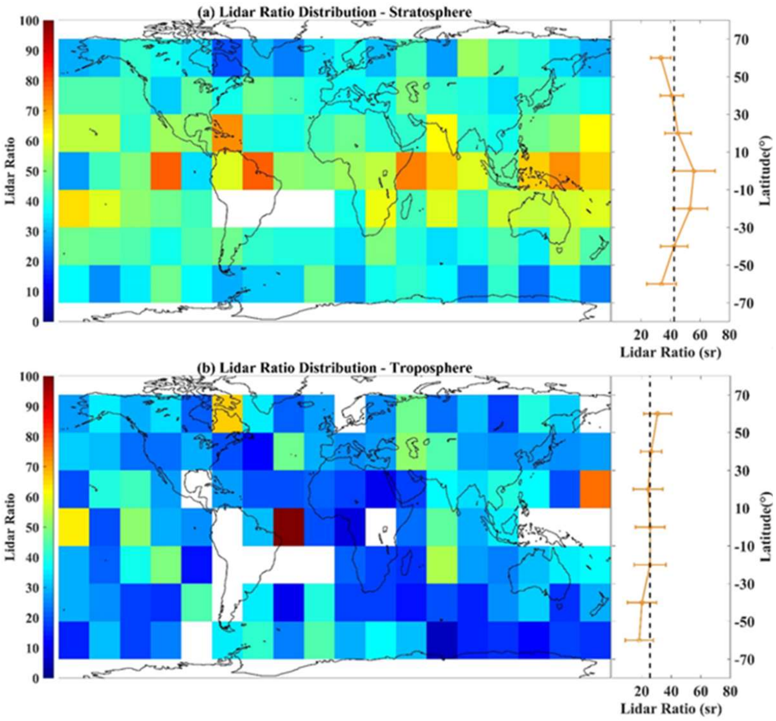

Figure 3. (a) Global stratospheric distribution of lidar ratios with a grid size of 20° x 20°. The color bar represents the lidar ratio value. The line on the right shows the median variation at 20° intervals from −70° to 70° (latitude) globally, and the error bar represents the median absolute deviation.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

Additionally, uncertainties in the extinction coefficient retrieval (including the lidar ration impact) were calculated to assess the reliability of the extinction results of undetected aerosol.

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.

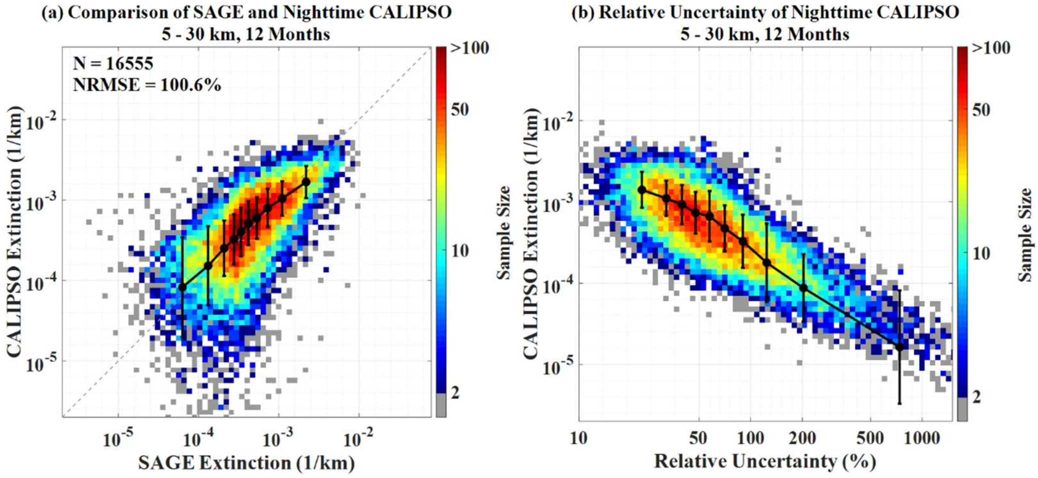

Figure 5. (a) Correlation plots of the retrieval within the matching grid of CALIPSO nighttime and SAGE III/ISS product from 5 km to 30 km for 12 months of validation. The color bar represents the sample size. The black bins represent the mean values of each 10% quantile (0-10%, 10-20%...and 90-100%)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

3. The CALIPSO retrieval of instantaneous faint aerosols is very challenging. Is there a useful way to improve the retrieval in the future, such as using a wavelet to denoise the CALIPSO level 1 data before retrieval? Although I do not recommend using denoising algorithms in the study of this paper because we prefer to do original research using the most formal methods first, I suggest discussing it for guiding future work.

Response: Thanks for your suggestion. Since the SNR of undetected aerosols in CALIOP instantaneous observations is very low, the denoising process is necessary to enable accurate retrieval, we have used a data pre-processing method consistent with Kim et al. (2017). As you say, a more efficient and disciplined denoising process is needed in the future and we have added a discussion of this in the article, as follows：

More effective data denoising processes can also be investigated to reduce biases in extinction retrieval, such as the systematic positive bias in the retrieval of daytime observations from CALIOP.

Specific comments

1. Line 23: “capture” should be “captures”.

   Response: Modified as per your suggestion.

2. Line 38: it is not always true to argue that the aerosol particules in the PBL “can usually be detected by CALIPSO”, which is inconsistent with previous findings. Therefore, this statement can be rephrased as “can only be detected by CALIPSO in the upper PBL in the absence of cloud (doi: 1016/j.atmosres.2016.05.010)”

   Response: Modified as per your suggestion, as follows:

   Aerosols are mostly concentrated in the planetary boundary layer (PBL), where optically thick aerosol layers occur and can usually be detected by the CALIPSO detection algorithm (Li et al., 2017; Kim et al., 2021; Guo et al., 2016).

3. Line 43: The citation may be corrected.

   Response: This paragraph has been reorganized and this sentence has been deleted.

4. Line 49: Clouds interact directly with surrounding aerosols, and in particular sub-cloud aerosols have a more significant effect on cloud production. However, these aerosols are not exactly the same as what the authors refer to as faint aerosol. A more rigorous and accurate expression is recommended.

   Response: Revisions have been made, as follows:

   However, clouds interact directly with ambient sub-cloud aerosol instead of near-surface heavy aerosol, the properties of which could be very different, especially for aerosol and ice cloud interactions (Rosenfeld et al., 2014).

5. Line 50: This study is not motivated by the aerosol proxy used for aerosol-cloud interaction. I think the ignorance of faint aerosol surrounding high-altitude cloud layers is the culprit to complex the quantification of aerosol climate effect. Therefore, “an improper aerosol proxy (such as AOD)” can be changed to “the ignorance of faint aerosols surrounding high-altitude cloud layers” or something like this.

   Response: Thank you for your suggestion, and the word has been revised as follows:

   Thus, the ignorance of faint aerosols surrounding high-altitude cloud layers causes large uncertainty in quantifying the climate effect of aerosols.

6. Line 68: “in” should be “since”.

   Response: Modified, as follows:

   The CALIPSO mission introduced new technology for retrieving aerosol profiles from space since April 2006,…

7. Line 73: It is recommended use the full name of the product (e.g. VFM) where it first appears in the manuscript.

   Response: Thank you for your suggestion, we have used the full name where it first appears in the revised manuscript, as follows:

   These aerosol layers should belong to a continuous one (shown in the red dashed box), but the Vertical Feature Mask (VFM) does not show the aerosol (~0.01 km^{-1}) between the two strong aerosol layers (~0.03 km^{-1}),…

8. Line 97: “vertical” should be “vertically”.

   Response: This is no longer an issue because the corresponding sentence has been changed to:

   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, …

9. Line 105: How is the SNR calculated here based on this formula?

   Response: In the revised manuscript it is further explained how the SNR is calculated and the statements are moved to Section 3.2 containing the SNR distribution graph, as follows:

   The SNR is calculated according to $SNR = \mu / \sigma$ based on the pre-processed TAB with 20 km horizontal resolution in the matching range, where μ and σ are the mean and the standard deviation of the signal, respectively.

10. Line 126: The matching of CALIPSO and SAGE considers spatial distances. What about temporal distances?

    Response: CALIPSO and SAGE observations within the same dates are matched, as specified in the revised manuscript as follows:

    Since only daytime data from SAGE III/ISS are available, the CALIPSO orbits are spatially and temporally matched to the nearest SAGE III/ISS observations on the same calendar date with the consideration for a smaller temporal-spatial variation of faint aerosol comparing strong aerosol at the near-surface.

11. Line 144: The "red dash boxed area" is not marked in the figure 3a.

Response: Modified, as follows:

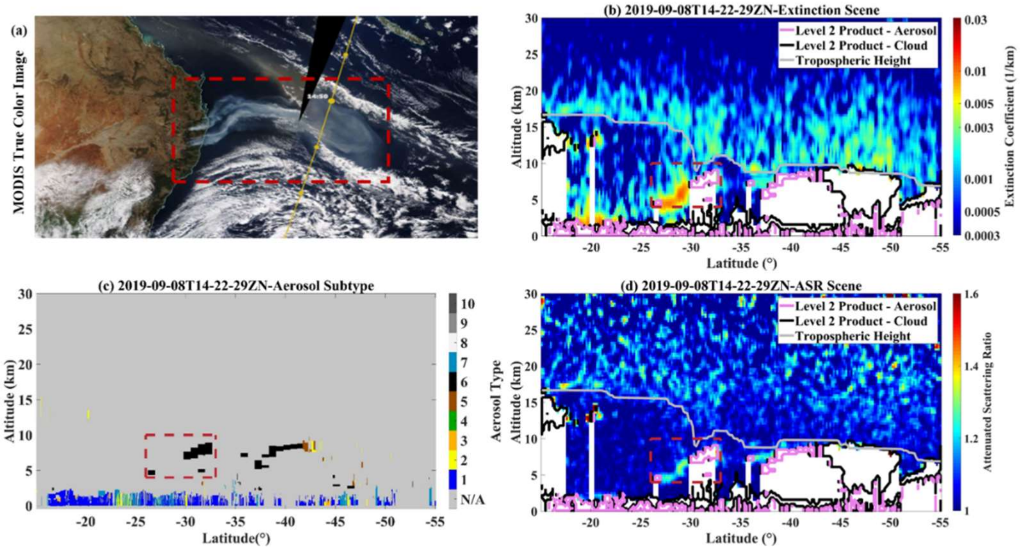

Figure 7. (a) MODIS Terra true-color image in the daytime and the passing CALIPSO track (yellow line) at night. (b) Latitude–altitude aerosol extinction of the corresponding nighttime CALIPSO track, same as in Figure 4a. The purple and black boundary lines and extinction inside represent the detected 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.

12. Line 163: Suggest reword "shows well the consistency" to "shows high consistency".

Response: Modified, as follows:

Figure 4b shows high-consistent extinctions of CALIPSO undetected aerosol and matched SAGE III/ISS 521 nm aerosol product (red dash line in Figure 4a) above 15 km.

13. Line 226: The range described here (60-10°N) does not correspond to the range of the red rectangular box in the diagram (40-10°N), and it is suggested to keep it consistent.

Response: Thanks for your careful review, it has been revised as follows:

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,…

14. Line 240: “and compared them” can be changed to “which are compared”

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

15. English should be further improved by a native English speaker.

    Response: Thanks for your suggestions, the English in the revised manuscript has been improved.

References

Fernald, F. G., Herman, B. M., and Reagan, J. A.: Determination of aerosol height distributions by lidar, Journal of Applied Meteorology and Climatology, 11, 482-489. 1972.

Fernald, F. G.: Analysis of atmospheric lidar observations: some comments, Applied optics, 23, 652-653. 1984.

Guo, J., Liu, H., Wang, F., Huang, J., Xia, F., Lou, M., Wu, Y., Jiang, J. H., Xie, T., and Zhaxi, Y.: Three-dimensional structure of aerosol in China: A perspective from multi-satellite observations, Atmospheric Research, 178, 580-589. 2016.

Hunt, W. H., Winker, D. M., Vaughan, M. A., Powell, K. A., Lucker, P. L., and Weimer, C.: CALIPSO lidar description and performance assessment, Journal of Atmospheric and Oceanic Technology, 26, 1214-1228. doi:10.1175/2009JTECHA1223.1, 2009.

Kacenelenbogen, M., Vaughan, M., Redemann, J., Hoff, R., Rogers, R., Ferrare, R., Russell, P., Hostetler, C., Hair, J., and Holben, B.: An accuracy assessment of the CALIOP/CALIPSO version 2/version 3 daytime aerosol extinction product based on a detailed multi-sensor, multi-platform case study, Atmospheric Chemistry and Physics, 11, 3981-4000. doi:10.5194/acp-11-3981-2011, 2011.

Kar, J., Lee, K.-P., Vaughan, M. A., Tackett, J. L., Trepte, C. R., Winker, D. M., Lucker, P. L., and Getzewich, B. J.: CALIPSO level 3 stratospheric aerosol profile product: version 1.00 algorithm description and initial assessment, Atmospheric Measurement Techniques, 12, 6173-6191. doi:10.5194/amt-12-6173-2019, 2019.

Khaykin, S. M., Godin-Beekmann, S., Keckhut, P., Hauchecorne, A., Jumelet, J., Vernier, J.-P., Bourassa, A., Degenstein, D. A., Rieger, L. A., and Bingen, C.: Variability and evolution of the midlatitude stratospheric aerosol budget from 22 years of ground-based lidar and satellite observations, Atmospheric Chemistry and Physics, 17, 1829-1845. doi:10.5194/acp-17-1829-2017, 2017.

Kim, M.-H., Yeo, H., Park, S., Park, D.-H., Omar, A., Nishizawa, T., Shimizu, A., and Kim, S.-W.: Assessing CALIOP-Derived Planetary Boundary Layer Height Using Ground-Based Lidar, Remote Sensing, 13, 1496. doi:10.1002/2016JD025797, 2021.

Kim, M. H., Omar, A. H., Vaughan, M. A., Winker, D. M., Trepte, C. R., Hu, Y., Liu, Z., and Kim, S. W.: Quantifying the low bias of CALIPSO's column aerosol optical depth due to undetected aerosol layers, Journal of Geophysical Research: Atmospheres, 122, 1098-1113. doi:10.3390/rs13081496, 2017.

Li, Z., Guo, J., Ding, A., Liao, H., Liu, J., Sun, Y., Wang, T., Xue, H., Zhang, H., and Zhu, B.: Aerosol and boundary-layer interactions and impact on air quality, National Science Review, 4, 810-833. doi:10.1093/nsr/nwx117, 2017.

Ma, P. L., Rasch, P. J., Wang, M., Wang, H., Ghan, S. J., Easter, R. C., Gustafson Jr, W. I., Liu, X., Zhang, Y., and Ma, H. Y.: How does increasing horizontal resolution in a global climate model improve the simulation of aerosol - cloud interactions?, Geophysical Research Letters, 42, 5058-5065. doi:10.1002/2015GL064183, 2015.

Rosenfeld, D., Andreae, M. O., Asmi, A., Chin, M., de Leeuw, G., Donovan, D. P., Kahn, R., Kinne, S., Kivekäs, N., and Kulmala, M.: Global observations of aerosol - cloud - precipitation - climate interactions, Reviews of Geophysics, 52, 750-808. doi:10.1002/2013RG000441, 2014.

Sakai, T., Uchino, O., Nagai, T., Liley, B., Morino, I., and Fujimoto, T.: Long - term variation of stratospheric aerosols observed with lidars over Tsukuba, Japan, from 1982 and Lauder, New Zealand, from 1992 to 2015, Journal of Geophysical Research: Atmospheres, 121, 10,283-210,293. doi:10.1002/2016JD025132, 2016.

Thomason, L. W., Pitts, M. C., and Winker, D. M.: CALIPSO observations of stratospheric aerosols: a preliminary assessment, Atmospheric Chemistry and Physics, 7, 5283-5290. doi:10.5194/acp-7-5283-2007, 2007.

Toth, T. D., Campbell, J. R., Reid, J. S., Tackett, J. L., Vaughan, M. A., Zhang, J., and Marquis, J. W.: Minimum aerosol layer detection sensitivities and their subsequent impacts on aerosol optical thickness retrievals in CALIPSO level 2 data products, Atmospheric Measurement Techniques, 11, 499-514. doi:10.5194/amt-11-499-2018, 2018.

Vernier, J.-P., Pommereau, J.-P., Garnier, A., Pelon, J., Larsen, N., Nielsen, J., Christensen, T., Cairo, F., Thomason, L. W., and Leblanc, T.: Tropical stratospheric aerosol layer from CALIPSO lidar observations, Journal of Geophysical Research: Atmospheres, 114. doi:10.1029/2009JD011946, 2009.

Winker, D., Tackett, J., Getzewich, B., Liu, Z., Vaughan, M., and Rogers, R.: The global 3-D distribution of tropospheric aerosols as characterized by CALIOP, Atmospheric Chemistry and Physics, 13, 3345-3361. doi:10.5194/acp-13-3345-2013, 2013.

Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K. A., Liu, Z., Hunt, W. H., and Young, S. A.: Overview of the CALIPSO mission and CALIOP data processing algorithms, Journal of Atmospheric and Oceanic Technology, 26, 2310-2323. 2009.

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