Response to Referee #2

General comments

In this contribution, Kar et al. present the new level 3 stratospheric aerosol product for the CALIPSO mission. The details of the science algorithm used to construct the level 3 product are presented. In addition, a preliminary quantitative assessment of the product is made through an inter-comparison of the CALIPSO and SAGE-III (ISS) extinction coefficient retrievals. Some nice observations of volcanic and wildfire smoke aerosols are also described. The paper is well structured and well written and the assumptions used in the retrieval are clearly articulated. This contribution is important because the level 3 aerosol product could potentially be used in radiative forcing studies that consider the impacts of aerosol loading in the stratosphere. I recommend publication after addressing some minor revisions suggested below.

Thanks very much for a careful reading of the manuscript and for your useful suggestions.

Specific comments

When describing the time-series of stratospheric perturbations due to major volcanic eruptions and wildfires shown in Figure 6, I think it's important to stress in the text (and Abstract) that this analysis is representative of aerosols in the tropical (25_S-25_N) stratosphere. Kasatochi and Sarychev were high latitude eruptions and so most of their sulfates were confined to mid-high latitudes. In addition, Kelud and Nabro are located within tropical latitudes and so their signatures are exaggerated relative to Kasatochi and Sarychev in the figure. Figure 6 would be much more illuminating if panels representing mid-high latitude bands were added.

Per your suggestion, we have revised this Figure (now Figure 7) with two new panels on mid-high southern (40^oS-60^oS) and northern latitudes (40^oN-60^oN). We have also revised the relevant sentence in the abstract as:

"Further, we show that the extinction profiles (retrieved using a constant lidar ratio of 50 sr) capture the major stratospheric perturbations in both hemispheres over the last decade resulting from volcanic eruptions, extreme smoke events, and signatures of stratospheric dynamics."

The discussion on the high bias of the CALIPSO retrievals relative to the SAGE-III retrievals is very interesting. Figure 13 shows that this is largely due to the assumption of a constant lidar ratio set to 50 sr in the CALIPSO product. The authors point out that there were 'probably no significant injections of ash from volcanoes' during their analysis period (June 2017 - August 2018); however, there was a significant (_0.15Tg SO2) eruption of Ambae (15.389_S, 167.835_E) in Vanuatu in April 2018 (Global Volcanism Program, 2018). This event may have affected the analysis and should be noted in the discussion section. Another point that could be mentioned is the effect of averaging the data over 15 months. Wouldn't this 'smooth out' the influence of volcanic/smoke aerosols on the derived lidar ratios shown in Figure 13?

Thank you for pointing this out. We have now replotted this figure (now Figure 14) by not using data from the biomass burning months of August through November 2017 and also all data after March 2018 to avoid contamination from the Ambae volcano. As can be seen in the revised figure, the results remain much the same despite loss of data.

Another factor that would impact the new aerosol product is the choice of the color ratio threshold. The authors use a color ratio threshold of 0.5 to remove clouds and retain volcanic ash clouds. However, several authors (Winker et al. 2012; Vernier et al. 2013; Prata et al., 2017) have shown that volcanic ash colour ratios can be as high as 0.80. Setting this threshold too low may therefore remove volcanic ash

from the 'all aerosol' product. This point should be addressed when introducing the choice of their selected threshold.

We have discussed this issue in detail in response to the first referee's comments. Essentially the problem stems from using one single hard number as threshold for all situations, which is what we have done for this first version of the stratospheric data product. Pueyhue Cordon Caulle (PCC) volcano had a large number of plumes with strong scattering. So using a larger threshold for the attenuated color ratio like 0.8 will capture more of those plumes. However, the larger particles with such high attenuated color ratios will sediment out relatively rapidly leaving more diffuse ash with low scattering ratios. As mentioned in the response to the first referee, at low scattering ratios there can be a significant overlap between the thin cirrus and aerosols. Using a attenuated color ratio threshold of 0.8 will thus include a larger contribution from the cirrus for the tenuous plumes for PCC. The problem will be exacerbated for other volcanoes with relatively tenuous plumes, since we use the same threshold for all cases. We found using the color ratio threshold of 0.5 does a reasonably good job of retaining the ash and sulfate plumes from PCC and Nabro volcanoes.

Specific comments about figures

In a lot of the figures the axes and colorbar labels are missing. Also some of the labels are not written clearly. For example, the authors use underscores and abbreviations. I think using proper label names with appropriate variable symbol definitions and units would make the figures clearer. Also latitude/longitude units should use the degree symbol (not the abbreviated 'deg'). At the very least, the labelling should be consistent throughout the paper.

We have addressed these issues in the revised version.

P1L28-30: There is also large disagreement (>100%) between CALIPSO and SAGE-III at altitudes below 20 km (Figure 11b). This should be stated in the abstract.

We have added the following to the abstract:

"Similarly there are large differences (≥100%) within 2 to 3 kilometers above the tropopause which might be due to cloud contamination issues."

P3L26: I see two Kar et al. (2018)s in the references section. Please use 'a' and 'b' to differentiate between them.

Done.

P4L10-11: 'The consequences of this change...' - I suggest adding the V3 zonally and vertically averaged attenuated scattering ratio (for the same time period) to Fig. 1. This would make the change from V3 to V4 very clear.

Per your suggestion we have now revised Figure 1. We are now showing the median values, as they better represent the distribution of CALIPSO data.

P4L17: Change 'over this latitude' to 'over each latitude'.

Done.

P5L17: 'accurate to about 1%' - do you have a reference for this?

It is actually 1.6% and we have corrected this in the revised version. This is from Kar et al. (2018a) and we have added the reference here.

P5L28: Delete 'going'.
P6L8: Replace 'i.e.' with 'such as'.

Done.

P6L11: 'Vaughan et al. (2009)' - Is there a new reference for the V4 level two layer detection algorithm that you could add?

The layer detection algorithm has not changed in version 4.

P6L14: Replace 'but' with 'however'.
P6L18: Change 'product' to 'level 3 stratospheric aerosol product'.
P6L21: Change 'the primary input files used for this product' to 'the primary input file used for the present product'.

Done.

P7, Figure 2: For consistency, should use small 'b' in the 'Write results to Background component' box.

Done.

P7L7: Please define the 'local tropopause'. E.g. is this taken from GMAO?

We have added the following:

"The tropopause heights were taken from the Modern-Era Retrospective analysis for Research and Applications 2 (MERRA-2) reanalyses as in all V4 products (Gelaro et al., 2017)."

P8L4: Change 'Antarctica' to 'Antarctic'. Change 'both the hemispheres' to 'both hemispheres'.

Done.

P9L24: Shouldn't this be 'Vernier et al. 2013'?

Actually it was first described in Vernier et al., 2009.

P9L25: The Puyehue ash did not reach 17 km. Maximum heights observed by CALIOP were _13 km (Vernier et al., 2013; Prata et al., 2017).

This sentence has been deleted in the revised version and the text has been restructured.

P9L26: Threshold of 0.5 seems too low. Vernier et al. (2013) use a threshold of 0.8 to discriminate between clouds and volcanic ash. I think the impact of this threshold should be mentioned (see specific comments above).

We have already responded to this above.

P10L11: Change 'threshold' to 'threshold of the level 2 layer detection algorithm'.

Done.

P11, Figure 4: Can you comment on what's causing the high scattering ratios just above 10 km at _50_N?

The first referee has pointed out that this could be due to the Grímsvötn volcano and we have added the following:

"Further, the high scattering ratios near 50ºN are likely due to the Grímsvötn volcano, which erupted in May 2011."

P12L3: What does this look like for a threshold of 0.75-0.80? You may get more of a signal for the Puyehue event.

As we mentioned above, taking a higher threshold also increases the cirrus contamination.

P12L4: Change 'Nabro' to 'Nabro (near 30_N)'.

Done.

P12, Figure 5: I think the labels are wrong here i.e. Figure 5b looks like 'background' and Figure 5a looks like 'all aerosol'.
P12L19-21: I don't see a high number of samples over North America in Figure 5b (see above Figure 5 comment).

Actually, the labels are correct, as can be verified from the attached color scale. In order to make it more clear and per the first referee's suggestion, we have now added an additional plot showing the difference in sample numbers between the two modes. We are now showing the sample number distribution at 17 km, showing enhanced sampling over the Asian summer monsoon plume area.

P13L27: Change 'significant ash' to 'significant ash and sulfate'.

Done.

P14L22: Change 'image' to 'figure'.
P14L23: Change '(Kasatochi, Nabro etc.) to '(e.g. Kasatochi and Nabro)'.

The text has been revised here in view of two new panels and these words do not appear in the new text.

P15L10: 'quite clearly seen' - I'm not sure it is that clear. There are several other features in the figure that are more apparent than the Black Saturday bushfires, which aren't commented on. I suggest changing to 'can be identified'.

Done.

P15, Figure 6: I think you could add panels representing middle and high latitude bands to better represent the major stratospheric perturbations on a global scale (see specific comments above). Also, there's a significant feature around December 2010 that's not mentioned. This was probably due to the Merapi (7.54_S, 110.446_E) eruption in Indonesia in November 2010. Surono et al. (2012) estimate 0.44 Tg of SO2 in the upper troposphere and the plume reached heights of 16-17 km. Another feature that's not explained is the one around July 2015. It seems quite significant. Do you know what's causing it?

Per your suggestion we have now added two new plots (now Figure 7) showing the stratospheric features at mid/high latitudes (40ºS-60ºS and 40ºN-60ºN). Originally we were only trying to point out the most prominent cases without cluttering it too much with labels. However we have now pointed out Merapi as well as some other features in the plot. The feature near July 2015 is the

signature of Calbuco volcano (also shown now in Figure 7). The Calbuco signature at these latitudes could be seen for several months afterwards.

P16, Figure 7d: Please fix the cropping at the bottom of the figure - some text has been cropped.

Done.

P16L15-16: 'irregular shapes' - could this also be due to ice particles?

While the differential attenuation strongly suggests these are mostly smoke particles, there is always the possibility of ice formation from the pyroconvection event. This sentence has been modified as:
"The high volume depolarization ratio (≥ 0.1) seen in Figure 7b is somewhat unusual for smoke and suggests the presence of irregular soot particles and mineral dust and possibly some ice particles, with fast adiabatic lifting possibly retaining the initial irregular shapes (Haarig et al., 2018, Khaykin et al., 2018)."

P17L6: 'smoke spreads globally' - I don't see this in the figure. It looks like the smoke spreads throughout the Northern Hemisphere but the Southern Hemisphere scattering ratio remains unchanged.

What we meant was that the plume spread at all longitudes and at lower latitudes---in any case "globally" has now been deleted and the new text reads as:

"After the original injection of smoke in August 2017 at mid-latitudes, the smoke spreads to lower latitudes as can be seen in these monthly mean spatial distributions from the level 3 stratospheric aerosol product."

P17, Figure 8: What is the cause of the high scattering ratio from 25-30 km over the equator?

The high scattering ratios at 25-30 km (now in Figure 9) reflect the tropical stratospheric reservoir. We have added the following:

"As in Figure 4, the feature with high attenuated scattering ratio near 25-30 km seen in all the four panels is the signature of the tropical reservoir of stratospheric aerosols, maintained by a complex interplay of transport from the troposphere and stratospheric dynamics as well as microphysical processes including the Brewer-Dobson circulation, the QBO, evaporation and sedimentation (Trepte and Hitchman, 1992, Kremser et al., 2016)."

P17L17: Kelud erupted in February 2014 not April 2014 (see Kristiansen et al., 2015).

Thank you—we have corrected this in the text.

P18L1: 'The gradual lofting of the plume from around 17 km over the tropics to nearly 24 km over several months...'. This seems to imply a rise of 7 km, which I think is misleading. Measuring from the top of the aerosol feature it looks like it rises from 21 to 24 km from March-December 2014 (a rise of 3 km). Please clarify this in the text.

We have now revised the sentence as:

"The gradual lofting of the plume, with its top rising from ~21 km over the tropics in March to ~24 km in the same general location several months later, shows the signature of stratospheric dynamics in the CALIPSO stratospheric aerosol product."

P19L7-9: The Calbuco volcanic cloud actually went almost directly through the SAA (see http://nicarnicaaviation.com/ calbuco-eruption-april-2015). Eventually it spread through the Southern Hemisphere but due to the rejection of data in the SAA region a large proportion of the Calbuco signal may not be captured in the CALIPSO level 3 stratospheric aerosol product. I think this is worth mentioning here.

We have revised the text as follows:

"The initial plumes would be missed out in the level 3 stratospheric aerosol product because data over the SAA region were not included. However the plumes quickly spread around the southern hemisphere in a belt between 60ºS to 30ºS (Lopes et al., 2019) and can be seen in the level 3 stratospheric aerosol product from May 2015 onwards for several months."

P20L18: Change 'essentially same' to 'essentially the same'.

Done.

P20, Equation (4): I got slightly confused here with the notation. What's the difference between $\alpha_p(r)$ (defined at P13L24) and $\sigma(z)_{CALIPSO}$? And which variable is the one that corresponds to the 'all aerosol' profile product?

Thanks for pointing out this oversight—we have replaced α by σ, which would make it consistent everywhere. The same variable will represent the extinction coefficient in both the components and for comparisons with SAGE III we have used only the "all aerosol" component, since the latter includes extinctions from all sources.

P22, Figure 11 caption: 'the mean 532 nm extinction coefficient' is this what $\sigma(z)_{CALIPSO}$ is? In Eq. (4) the definition is the 'extinction coefficient at altitude z'. I would use the same wording to avoid confusion or put the symbols ($\sigma(z)_{CALIPSO}$ and $\sigma(z)_{SAGE}$) in parentheses in the figure caption.

The extinction coefficient as a function of altitude is σ(z) with subscripts either CALIPSO or SAGE. The curves in Figure 11 (now Figure 12) represent the mean taken over all the profiles of σ(z) using all the data as mentioned in the legend. We think it is generally clear.

P22L18: 'the presence of clouds which may impact the retrievals' - Please provide a little more information on how clouds impact the retrieval. If some clouds weren't removed, wouldn't this bias SAGE-III aerosol extinction high? Thus compensating for the difference seen in the comparison with CALIPSO below 20 km?

In the revised version, we have discussed the possible impacts of cloud clearance issues in our product in section 2.2.1 and added a new figure (Figure 4). Further we have added the following "As pointed out in section 2.2.1, the filtering scheme that removes thin cirrus clouds in the all aerosol mode is not as efficient as the technique employed in the background mode. Consequently, scattering artifacts from undetected subvisible cirrus are more likely to appear in the all aerosol mode in the tropical lower stratosphere within a few kilometers above the tropopause. Using the

extinction profiles from the background mode reduces the differences at these altitudes but does not completely eliminate them (not shown)."

P22L23: Change '2.0' to '2'.

Done.

P22L24: On my first read through, I immediately thought the assumption of constant lidar ratio was the issue. You go on to discuss this but it's not mentioned here. Perhaps it's worth adding a sentence and referencing the discussion that comes later.

We have added the following:

"We further discuss the possible issues resulting from uncertainties in lidar ratios below."

P23L15: Change 'Discussion:' to 'Discussion'.

Done.

P24L3-5: Change 'tropical latitudes' to 'tropical latitudes (30_S–30_N)'.

Done.

P24L5: Change 'higher latitudes' to 'higher latitudes and lower altitudes'.

Done.

P24L10: 'smoke, marine aerosols etc' - please list all the aerosol types considered by references cited.

All the different types of aerosols in the troposphere are really not relevant in the stratosphere, so we have simply deleted "such as smoke, marine aerosols etc."

P24, Eq. (5): In Eq. (3), the two-way particulate transmittance is range-dependent. I assume it would be range-dependent ($T_{2p}(r)$) here too?

Thank you and this has been corrected.

P25L16: 'substantially lower' - Could you put a number to this? E.g. what's the mean lidar ratio in the lowermost stratosphere? I think it is important to give a number or range given the discussion that follows.

We have added "≤ 40 sr" to incorporate both the lowermost stratosphere as well as the high latitudes.

P27L3: 'no significant injections of ash from volcanoes' - this is probably true, but there were significant injections of SO2 and therefore sulfate. For example, Ambae (Vanuatu) in April 2018 underwent a significant SO2-rich eruption (see specific comments above).

We have now revised Figure 13 (now Figure 14) by removing possibly contaminated data from the pyroCb event of 2017 and all data after March 2018 to avoid effects from Ambae volcano.

P27L12: Change 'volcanic eruptions' to 'volcanic eruptions and wildfires'.

Done.

P27L16: Change ‘mid-to-high latitudes’ to ’mid-to-high latitudes (30_S–60_S and 30_N–60_N)’

Done.

P27L16: Change ’high altitudes’ to ’high altitudes (10–20 km)’

Done.